

Field Test and Evaluation of Residential Ground Source Heat Pump Systems Using Emerging Ground Coupling Technologies

Final Report

February 2013

Prepared by
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Oak Ridge National Laboratory

**FIELD TEST AND EVALUATION OF
RESIDENTIAL GROUND SOURCE HEAT PUMP SYSTEMS USING
EMERGING GROUND COUPLING TECHNOLOGIES**

FINAL REPORT

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Jeffrey Munk

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EXECUTIVE SUMMARY

An applied research initiated and coordinated by Oklahoma Gas and Electric Company (OG&E) demonstrated that the required borehole depth of vertical closed-loop ground heat exchangers (GHXs), which are predominantly used in ground source heat pump (GSHP) applications, can be reduced by up to 36% using alternative configurations.

In order to identify new technologies and techniques that can reduce the upfront costs of GSHP systems and thus make them more affordable to its customers, OG&E initiated this applied research project in 2011 in collaboration with the International Ground Source Heat Pump Association (IGSHPA), Oak Ridge National Laboratory (ORNL), and other stakeholders of the GSHP industry. A field test was conducted at ten nearly identical homes in a Habitat for Humanity community in Oklahoma City to study the performance of alternative configurations of GHX, which include eight different combinations of new heat exchanger designs, new grouting materials, and various drilling techniques.

ORNL analyzed the performance of the tested GHXs as well as the associated GSHP systems. In addition, ORNL assessed the impacts of these alternative configurations on the required borehole depth through computer simulations. Among the many informative observations derived from this study are the following findings:

- The GSHP systems using the new GHXs successfully maintained the room temperature at the setpoint specified by individual homeowners during the one-year test period (from October, 2011 through September 2012) except in one test home (unit 9), where the building cooling load exceeded the capacity of the installed 2-ton GSHP system.
- The GSHP system efficiency in heating season, valued with Coefficient of Performance (COP), ranged from 3.8 to 4.5 at the ten test homes and the differences in the COP were attributable to individual homeowners' thermostat settings; the system efficiency in cooling season, valued with Energy Efficiency Ratio (EER), varied widely from 9.3 to 18.7 among the test homes. Except in two homes (units 1 and 9), where the GHX was apparently undersized, the system EERs were all above 14.7 during the second hottest summer in the history of Oklahoma City¹. The discrepancy in system EERs was a result of the wide variation of the leaving fluid temperature from the GHXs during the cooling season.
- The monthly peak electricity demand of the installed 2-ton GSHP systems varied from 1.8 to 2.2 kW during the heating season and it varied from 1.6 to 2.6 kW during the cooling season. The variation in peak electricity demand are attributable to different operating conditions and the variable-speed circulation pump used in the GSHP systems, which were controlled to maintain a constant differential temperature across the GHX. The spike in summer peak electricity demand in unit 9 (2.6 kW) was due to the unexpected high internal heat gain in this particular home.
- The energy consumption of the tested GSHP systems varied significantly among these nearly identical test homes and were affected by many factors, including room temperature (especially in winter, when the room temperature significantly affected the heating load of the test homes), the fluid temperature of the GHXs, and the thermostatic control.

¹ Oklahoma City had 18 straight days where temperatures reached 100° or greater, including three days in a row that were 112°, exacerbating wildfires and drought in the state. (<http://climatecommunication.org/new/articles/summer-of-extremes/overview/>).

- Both the field tests and the computer simulations concurred that the double U-tube GHX requires 36% less borehole depth compared with a conventional single U-tube GHX while retaining same performance at given building load and ground condition [with a 1.85 Btu/(hr-ft-°F) thermal conductivity]. Other new GHXs being tested also show the potential to reduce the required borehole depth, although the reductions are smaller (20-30%). A larger reduction in required borehole depth can be expected at locations where the ground has better thermal conductivity, as shown in Fig. E1.

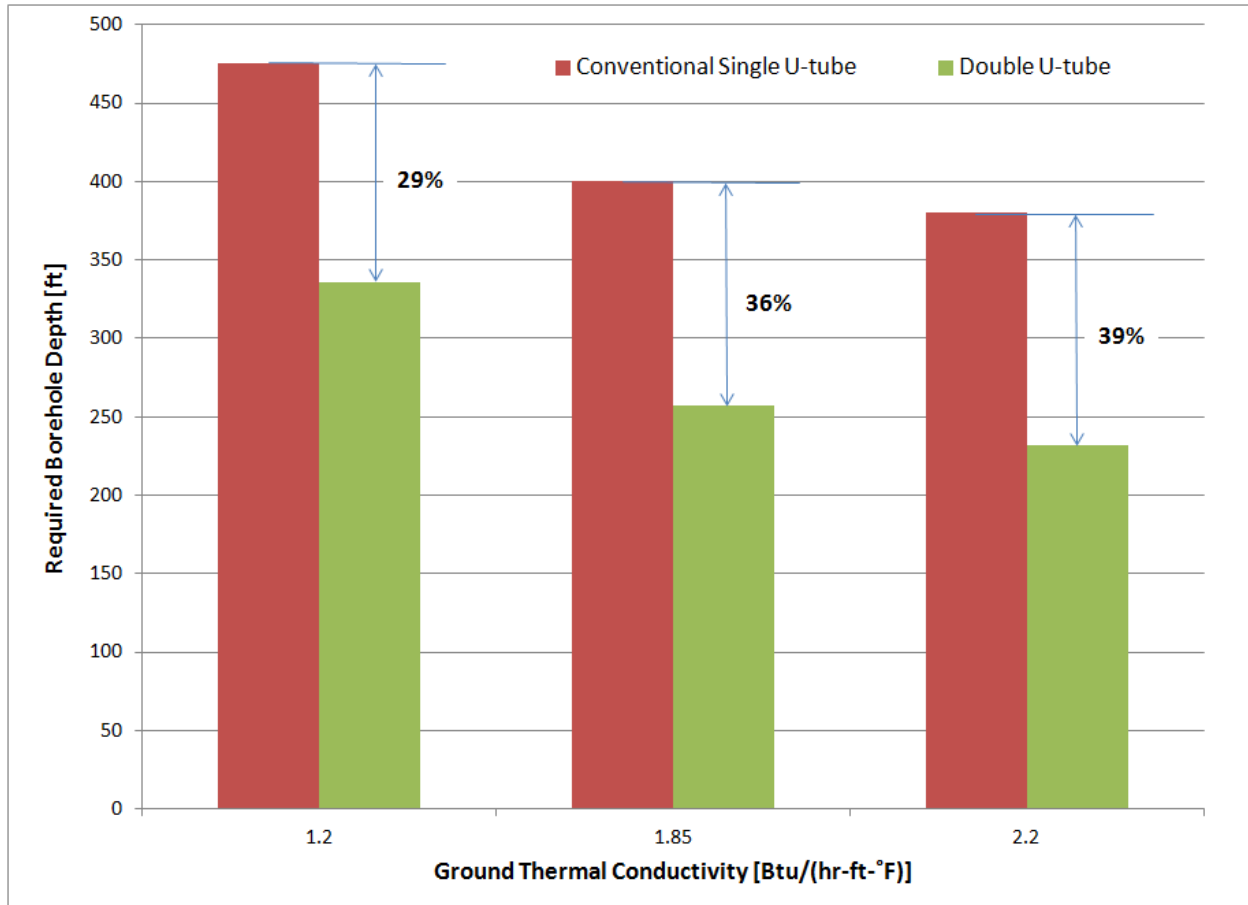


Fig. E1. Comparison of reduced borehole depth at different ground conditions.

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1. INTRODUCTION

Ground source heat pump (GSHP), often referred as “geothermal heat pump” or “geo-exchange heat pump”, is a technology that makes use of low-grade and renewable resources—including the shallow surface of the ground, groundwater, surface water bodies, or even municipal wastewater—as heat sinks/sources for the heat pump to provide space conditioning and water heating. It is one of the most energy-efficient technologies for space conditioning and/or water heating. In addition to reducing the energy costs of building owners, GSHPs can reduce summer peak electric demand and improve the load factor for electric utilities. The vertical closed-loop ground heat exchanger (GHX), which consists of a vertical borehole with a set of pipes inserted in it, is predominantly used in GSHP systems in the United States. Because of the relatively high cost of the GHX, the application of GSHP technology is limited in the United States. If the cost of the GHX can be reduced without sacrificing its performance, GSHP systems will be adopted on a much larger scale in the United States.

Oklahoma Gas and Electric Company (OG&E), an electric public utility providing electrical service in the states of Oklahoma and Arkansas, realized the potential benefits of large-scale application of GSHP systems and initiated a research and development project to identify new technologies and techniques that can reduce the upfront costs of GSHP systems and thus make them more affordable to its customers. In collaboration with the International Ground Source Heat Pump Association (IGSHPA), Oak Ridge National Laboratory (ORNL), and other stakeholders of the GSHP industry, a field test was conducted at ten nearly identical homes in a Habitat for Humanity community in Oklahoma City to investigate the performance of alternative configurations of GHX, which include eight different combinations of new heat exchanger designs, new grouting materials, and various drilling techniques. ORNL was invited to monitor and evaluate the performance of the tested GHXs and the associated GSHP systems. In addition, based on the monitored performance data, ORNL will assess the impacts of these new technologies on the required drilling depth for boreholes through computer simulation of the residential GSHP systems. The field test and assessment will verify the benefits of these new technologies, reduce the risk of failure for installation contractors, and if successful, provide an impetus toward further commercialization of these technologies.

Various industry partners provided the new heat exchangers, grouting materials, drilling services, and in-situ tests of ground thermal conductivity and the borehole thermal resistance of the new GHXs. The field test was conducted at ten nearly identical homes in a Habitat for Humanity community in Oklahoma City. The conditioned floor space of each home is about 1,200 ft², and each home already has a 2ton GSHP system that uses a 400 ft deep conventional vertical, single U-tube GHX. Figure 1 illustrates the configuration of the existing GSHP system and a few energy-saving features of the homes (Ellis 2008). Before the field test, the heat pump equipment in each of the test homes was replaced with a new unit by ClimateMaster, and eight new GHXs were sized to match the original GHX and installed in eight different homes, respectively. The test also includes two other homes that use the original GHX as reference cases.²

In Section 2, the new GHXs being tested are briefly introduced. The data collection and performance metrics used to evaluate the GSHP systems are described in Section 3. Section 4 summarizes the measured performance of the ten residential GSHP systems in a heating season (December 2011 through February 2012) and a cooling season (June 2012 through August 2012). An assessment of the potential borehole depth reduction resulting from the new GHXs is presented in Section 5. Finally, Section 6 summarizes the main conclusions drawn from this study.

² One of these two reference cases was monitored only for heating season performance.

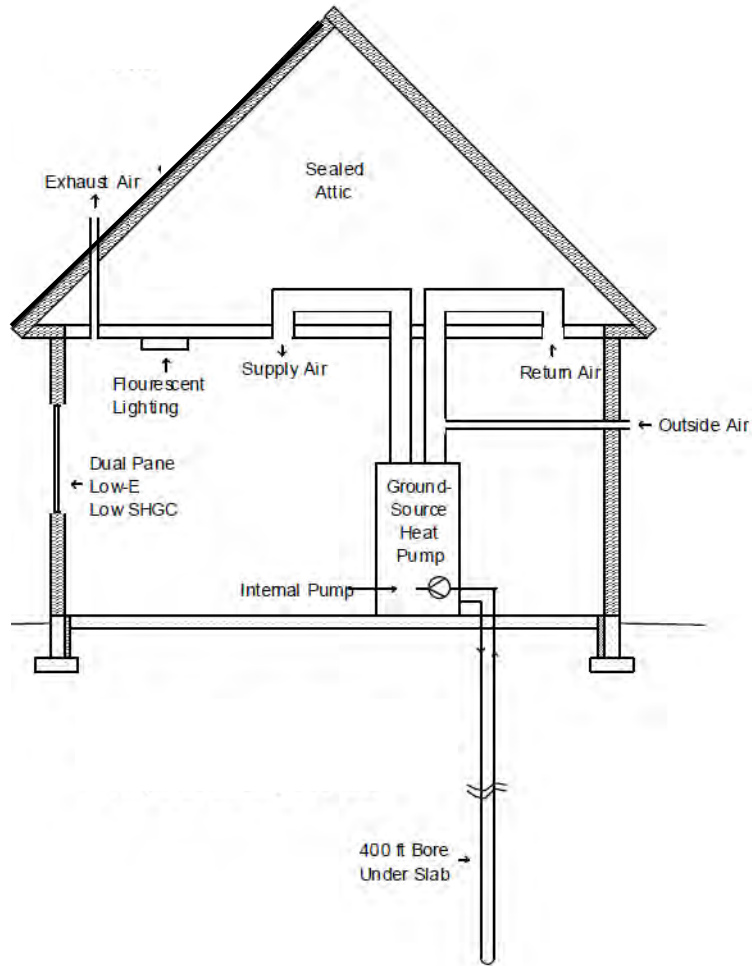


Fig. 1. An illustration of the existing GSHP system and a few energy-saving features in the test homes. Source: (Ellis 2008).

2. DESCRIPTION OF TESTED GHXS

The new GHXs being tested in this study are eight different combinations of various grouting materials, drilling technologies, and heat exchanger pipes. The grouting materials include Barotherm® Gold (with nominal thermal conductivity of 1.0 Btu/h·ft·°F), Barotherm Max (with nominal thermal conductivity of 1.6 Btu/h·ft·°F), and common bentonite chips (with nominal thermal conductivity of 0.43 Btu/h·ft·°F). The drilling technologies include mud rotary, air rotary, mud sonic, and air sonic. The heat exchanger pipes include single U-tube, double U-tube, and two different coaxial configurations.

In a single U-tube layout (Fig. 2a), the circulating fluid flows down one leg of the U-tube and flows up the other. The space between the pipes and the borehole wall is filled with grout to prevent water and contaminants from migrating along the vertical borehole. The double U-tube layout (Fig. 2b) is connected in parallel so that water flow is divided between the two U-tube pipes evenly. As in the single U-tube layout, the space between the pipes and the borehole wall is filled with grout.

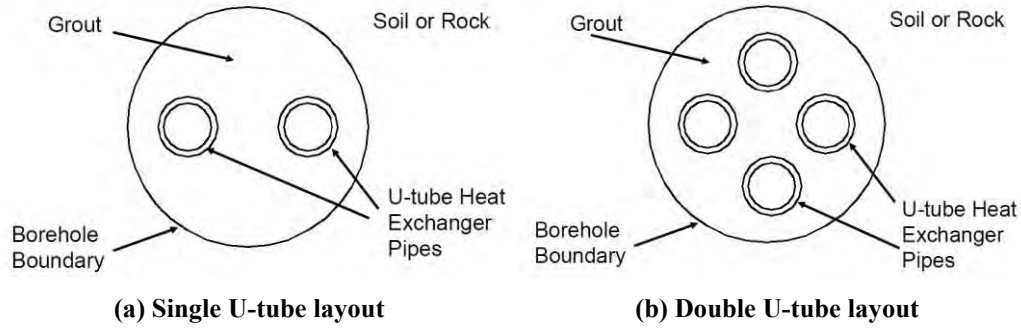


Fig. 2. Illustration of single and double U-tube configurations.

In a coaxial configuration, an internal pipe is placed inside a larger external pipe. Grout fills the space between the external pipe and the borehole wall. The fluid enters the heat exchanger through either the internal pipe or the annulus and flows downward, and then travels upward through the other pathway. The coaxial pipes tested in this study were provided by two separate suppliers. They are engineered with special technologies (i.e., a helix adhered to the outside wall of an insulated internal pipe as shown in Fig. 3a, or a corrugated external plastic pipe with a high-density polyethylene [HDPE] internal pipe and a stab-type plug-in connection at the end of the pipes, as illustrated in Fig. 3b). In all the coaxial configurations tested in this study, the fluid enters through the internal pipe and exits through the annulus.

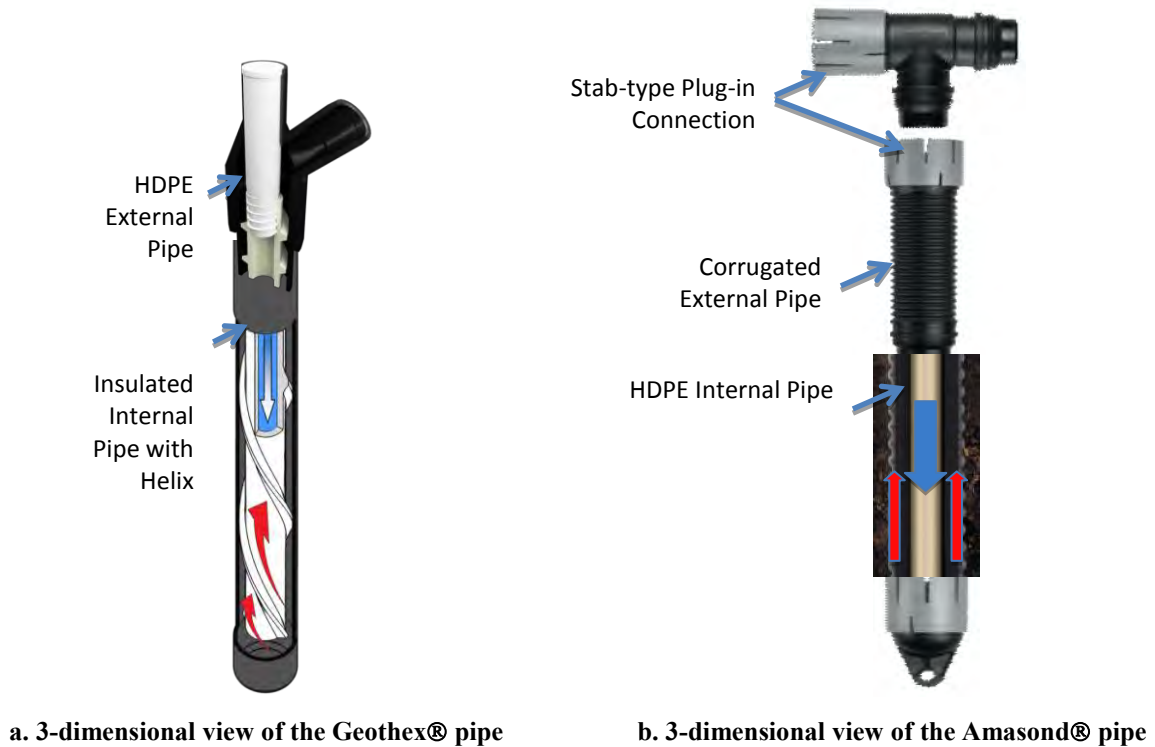


Fig. 3. Illustration of various co-axial pipes tested in this study.

Table 1 summarizes the parameters of all ten of the GHXs included in this study. The borehole depth and diameter, grouting material, and drilling techniques used in each of the eight new GHXs were specified with the intention of making the new GHXs equivalent to the original GHX, which is a 400 ft deep vertical single U-tube heat exchanger grouted with conventional bentonite.

Table 1. Information for the tested new GHXs and the original GHX

Unit number	1	2	3	4	5	6	7	8	9	10	
GHX type	Co-axial	Single U-tube	Co-axial	Co-axial	Double U-tube	Double U-tube	Single U-tube	Single U-tube	Co-axial	Single U-tube	
GHX supplier	Amasond®	Existing loop	Amasond	Geothex®	Geo-Enterprises	Geo-Enterprises	Geo-Enterprises	Existing loop	Geothex	Ewbank	
Grout type	Barotherm® Gold	Bentonite	Barotherm Max	Barotherm Max	Barotherm Gold	Barotherm Gold	Barotherm Gold	Bentonite	Barotherm Gold	Gravel/ bentonite pellets	
Grout thermal conductivity, Btu/(h·ft·°F) ; (W/[K·m])	1.0 (1.5)	Estimated 0.4 (0.6)	2.95 (5.11) ^a	1.79 (3.10) ^a	1.0 (1.5)	1.0 (1.5)	1.0 (1.5)	Estimated 0.4 (0.6)	0.83 (1.44) ^a	0.43 (0.74) [Top 50 ft of borehole]	
Drilling technique	Mud rotary	Air rotary	Air rotary for one hole and mud rotary for the other two holes		Sonic mud	Mud rotary	Mud rotary	Sonic air	Air rotary	Mud rotary	Mud rotary
Borehole diameter, in. (mm)	5.25 (133)	Unknown	5.25 (133)	5.25 (133)	5.25 (133)	5.25 (133)	4.75 (120)	Unknown	4.75 (121)	2.75 (70)	
Active borehole depth ft (m)	2×150 (46) ^b	400 (122)	3×120 (37) ^b	214 (65)	260 (79) ^c	260 (79) ^c	319 (97)	400 (122)	2×150 (46) ^b	2×180 (55)	
Total pipe length, ft (m)	300 (92)	400 (122)	360 (111)	214 (65)	520 (158)	520 (158)	319 (97)	400 (122)	300 (92)	360 (110)	
Internal pipe outer diameter, in. (mm)	1.495 (38)	1 (25) HDPE	1.495 (38)	1.61 (41)	0.75 (19) PEX	0.75 (19) HDPE	1 (25) HDPE	1 (25) HDPE	1.61 (41)	1 (25)	
Internal pipe inner diameter, in. (mm)	1.20 (30)	0.860 (22)	1.20 (30)	1.10 (28)			0.860 (22)	0.860 (22)	1.10 (28)	0.860 (22)	

Table 1. Information for the tested new GHXs and the original GHX (continued)

Unit number	1	2	3	4	5	6	7	8	9	10
Internal pipe wall thermal conductivity, Btu/(h·ft·°F); (W/[K·m])	0.225 (0.389)	0.225 (0.389)	0.225 (0.389)	0.0081 (0.014)	0.225 (0.389)	0.225 (0.389)	0.225 (0.389)	0.225 (0.389)	0.0081 (0.014)	0.225 (0.389)
External pipe outer diameter, in. (mm)	Max 2.47 (63) Min. 2.21 (56)	NA	Max 2.47 (63) Min. 2.21 (56)	2.48 (63)	NA	NA	NA	NA	2.48 (63)	NA
External pipe inner diameter, in. (mm)	Max 2.26 (57) Min. 2.01 (51)	NA	Max 2.26 (57) Min. 2.01 (51)	2.24 (57)	NA	NA	NA	NA	2.24 (57)	NA
External pipe wall thermal conductivity, Btu/(h·ft·°F); (W/[K·m])	0.225 (0.389)	NA	0.225 (0.389)	0.225 (0.389)	NA	NA	NA	NA	0.225 (0.389)	NA
Undisturbed soil temperature, °F (°C)	63.0 (17.2)	63.0 (17.2)	63.0 (17.2)	63.0 (17.2)	63.4 (17.4)	63.4 (17.4)	63.7 (17.6)	63.0 (17.2)	63.0 (17.2)	63.0 (17.2)
Soil thermal conductivity, Btu/(h·ft·°F); (W/[K·m])	Unknown	Unknown	1.85 (3.2) ^d	1.83 (3.17) ^d	Unknown	2.07 (3.58) ^d	2.22 (3.84) ^d	Unknown	1.60 (2.77) ^d	1.72 (3.00) ^d

^a From a lab test of the sample grout obtained at the installation cite within 48 hours.

^b The multiple coaxial pipes in units 1, 3, and 9 are connected in series.

^c The two single U-tube pipes in units 5 and 6 are connected in parallel and inserted in the same borehole.

^d Measured with in-situ test after the new GHX was installed.

A15% methanol-water solution was used as heat carrier fluid in all of the new GHXs. The flow rate of the heat carrier fluid in each of the GHXs varied during heat pump operation by the variable-speed circulation pump used in the new heat pump unit, which was controlled to maintain a constant differential temperature across the GHX.

3. DATA COLLECTION AND PERFORMANCE METRICS

The data acquisition system was designed and built by OSU/IGSHPA research personnel. The data system included a custom designed signal conditioning board and data module that accommodated the following sensors:

- Two 10K ohm thermistor temperature probes for inlet and outlet fluid temperatures of the tested GHXs matched and calibrated to better than 0.1°F,
- Measurement Specialties series HTM2500 relative humidity and temperature probe for indoor return air (measured at the duct inside the closet where the GSHP unit is installed),
- Wattnode WNP-3Y-208P from Continental Control Systems for measuring power draw of GSHP units, circulating pump, and de-superheater pump,
- Ground loop flow rate readings from the internal flowmeter of the tested GSHP units.

Data was measured at every second and recorded at 1 minute intervals on a netbook configured with a version of Linux and saved in a comma separated value (.csv) form. Data was uploaded to a network server from the netbook through a Verison wireless modem. A separate data acquisition system was installed on each home monitored.

The following performance metrics are determined from the measured data:

- Monthly total power consumption of the GSHP system
- Monthly peak electric demand of the GSHP system
- Monthly average GSHP system efficiency (coefficient of performance [COP] for heating and energy-efficiency ratio [EER] for cooling)
- Monthly average room temperature (when the GSHP system is on)
- Monthly average GHX fluid temperature (when the GSHP system is on)

The monthly average COP (\overline{COP}) and monthly average EER (\overline{EER}) of a GSHP system are determined with the total heating/cooling output and the total electric consumption of the GSHP system during a particular month, as expressed in Eqs. (1) and (2), respectively.

$$\overline{COP} = \frac{\sum_{i=1}^n QH(i)}{\sum_{i=1}^n P_{HP_H}(i) \times 3.413} = \sum_{i=1}^n \frac{P_{HP_H}(i)}{\sum_{i=1}^n P_{HP_H}(i)} \times COP(i) \quad (1)$$

$$\overline{EER} = \frac{\sum_{i=1}^m QC(i)}{\sum_{i=1}^m P_{HP_C}(i)} = \sum_{i=1}^m \frac{P_{HP_C}(i)}{\sum_{i=1}^m P_{HP_C}(i)} \times EER(i) \quad (2)$$

where $QH(i)$ and $QC(i)$ are the heating and cooling outputs at the i^{th} minute in the month when the GSHP system is running; $P_{HP_H}(i)$ and $P_{HP_C}(i)$ are the coincident power consumption of the GSHP system; n and m are the total number of minutes when the system runs in heating and cooling modes, respectively, in the month.

As shown in Eqs. (1) and (2), the monthly average COP and EER are the power-weighted averages of the instantaneous COP and EER values measured each minute when the GSHP system is running in the month.

QH and QC (in Btu/Hr) at each minute are calculated with ground loop side measurements as shown in Eqs. (3) and (4), respectively:

$$QH = GL_{SH} \times GL_{FL} \times (GL_{LFT} - GL_{EFT}) + P_{HP} \times 3.413 \quad (3)$$

$$QC = GL_{SH} \times GL_{FL} \times (GL_{EFT} - GL_{LFT}) + Q_{DSH} - P_{HP} \times 3.413 \quad (4)$$

where, GL_{SH} is the specific heat of the heat carrier fluid (in Btu/Lb·°F); GL_{FL} is the mass flow rate of the heat carrier fluid in the ground loop (in Lb/Hr); GL_{LFT} and GL_{EFT} are the leaving and entering fluid temperatures of the ground loop (in °F), respectively; P_{HP} (in W) is the power draw of the entire GSHP system (including heat pump compressor, circulation pump, desuperheater pump, and fan of the air distribution system) at the minute; and Q_{DSH} is the heat transfer rate through the desuperheater of the heat pump to preheating domestic hot water.

4. SUMMARY OF MEASURED PERFORMANCE METRICS

This section summarizes the performance metrics of the tested GSHP systems in both heating and cooling season. As a result of several severe weather events and the resulting failure of the data acquisition systems, some data were missing in a few test homes during the test period. In addition, the flow meters for measuring the ground loop (fluid) flow rate in three tested homes (units 4, 6, and 7) were unable to produce valid measurements through most of the test period, despite several flow meter replacements and repairs. As a result, the system COPs and EERs of the GSHP systems in these test homes could not be determined for most months during the test period. The measured data at each individual GSHP system in each month are presented in graphical format in Appendix B.

4.1 HEATING SEASON

The hourly ambient dry-bulb temperature measured at the Will Rogers International Airport of Oklahoma City from December 2011 through March 2012 is plotted in Fig. 4. These data are from the National Oceanic Atmospheric Administration (NOAA). The ambient dry-bulb temperature averaged 42.8°F and fluctuated between 17.1 and 73.0°F during the heating season.

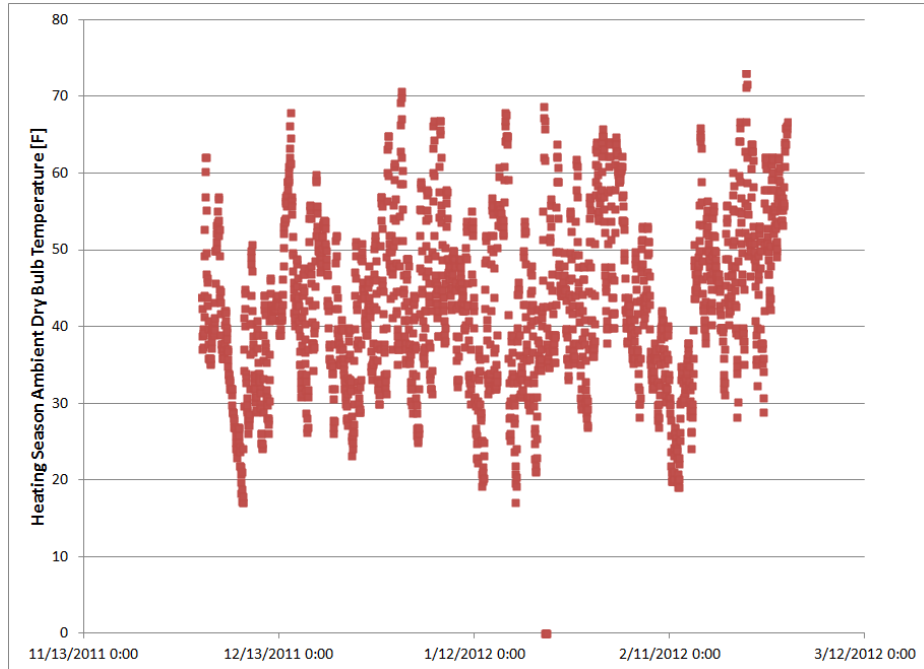


Fig. 4. Ambient dry-bulb temperature in the 2011–2012 heating season measured at Will Rogers International Airport of Oklahoma City.

4.1.1 Operating Conditions

For the GSHP systems tested in this study, in which a water-to-air heat pump unit is used, the operating conditions included the temperature and the humidity of the return air, and the entering water temperature, which is the leaving fluid temperature (LFT) from the GHX of the GSHP system.

As shown in Fig. 5, the monthly average room temperatures in the ten test homes were different and ranged from approximately 67 to 79°F. However, for each individual home, the room temperature was maintained at a relatively constant level (less than 2°F variance) during the entire heating season. Detailed minutely measurements indicated that the GSHP systems were able to warm each home to the thermostat setpoint specified by the homeowner and maintain the temperature during the heating season.

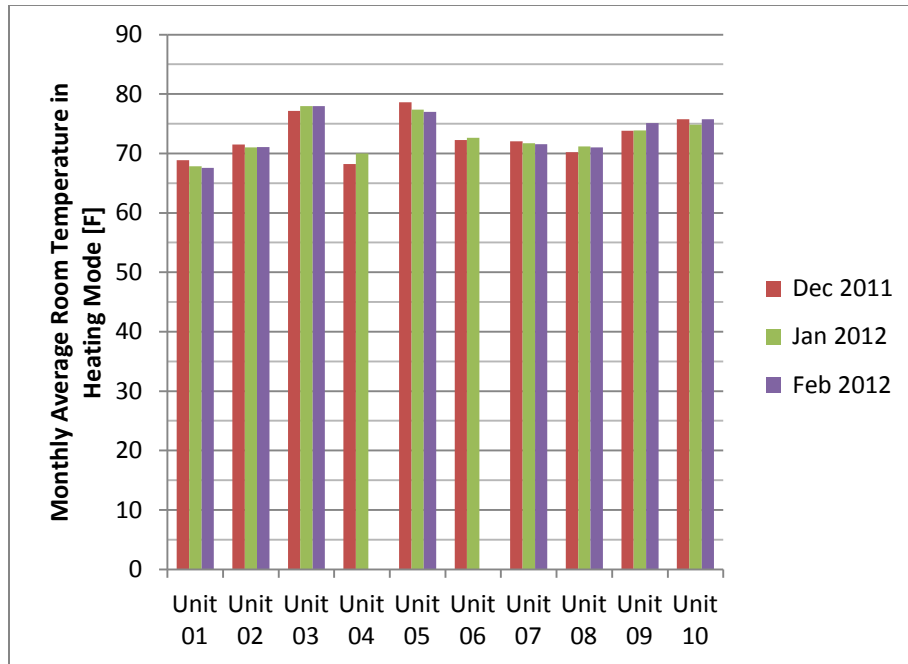


Fig. 5. Monthly average room temperature maintained by the GSHP system in each room (measured when the GSHP systems were operating in heating mode).

The monthly average GHX LFTs of the 10 GSHP systems were in the 51– 59°F range during the heating season, as shown in Fig. 6. The GHX LFT of each system decreased slightly (by less than 5°F) during the heating season, except in units 4 and 6. The monthly average GHX LFTs in all the test homes other than unit 4 were within a narrow range (varying by less than 6°F) in each of the three months.

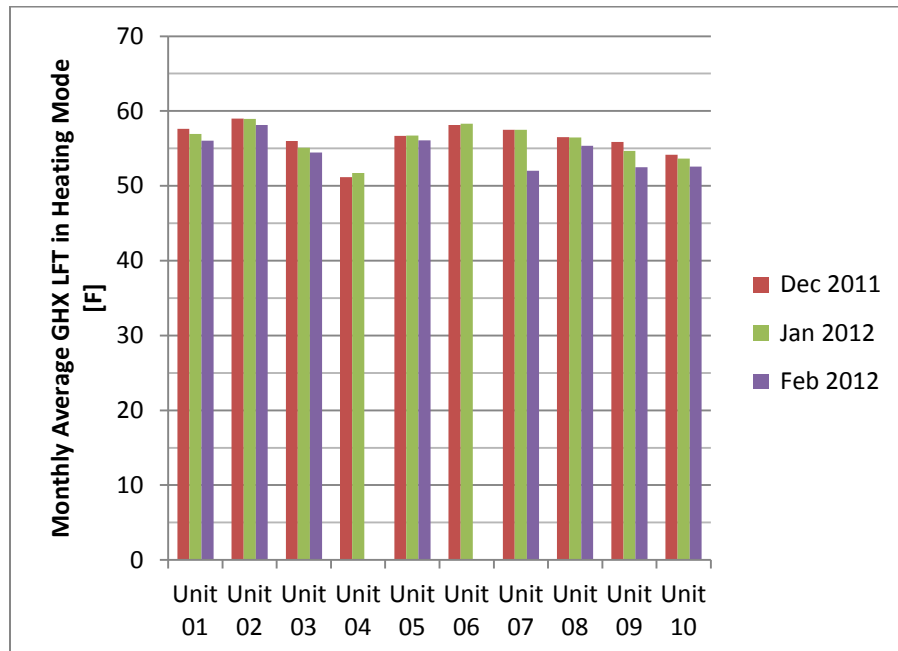


Fig. 6. Monthly average LFT from the GHX of each GSHP system (measured when the GSHP systems were operating in heating mode).

4.1.2 System COP

The GSHP system COP in each minute (when the system was running) is calculated with Eq. 5. In this equation, the total heating output of the GSHP system (Q_H), which is calculated with Eq. 3, include the heat for preheating the domestic water through the desuperheater. The monthly average COP (\overline{COP}) is calculated with Eq. 1.

$$COP = \frac{Q_H}{P_{HP}} \quad (5)$$

The system COPs in units 4, 6, and 7 were not available during the three months because of a lack of valid flow rate measurements and/or missing power consumption data.

As shown in Fig. 7. GSHP systems COPs ranged from 3.8 to 4.5 during the heating season and the COP of a particular GSHP system decreased only slightly (less than 10%) during the heating season. These numbers are slightly lower than the COP (4.62 at full load condition and 4.93 at part load condition) provided in the manufacturer's catalog when the entering fluid temperature is at 50°F (see Appendix A). The difference is thought due to the different pump power and fan power than that used in generating the catalog data.

As shown in Fig. 8, the 9.4°F increase in average room temperature between units 1 and 5 (67.6 vs. 76.9°F) resulted in a 12.5% decrease in the system COPs (4.5 in unit 1 vs. 4.0 in unit 5). The average GHX LFTs of the two GSHP systems were almost the same (56 vs. 55.9°F).

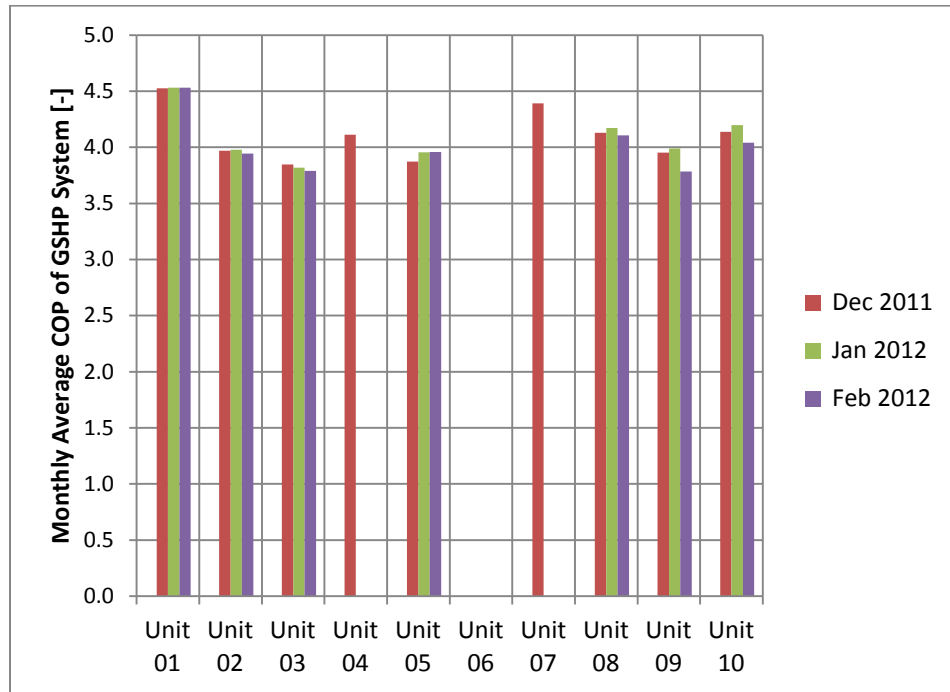


Fig. 7. Monthly average COPs of the GSHP systems.

Figure 8 does not show a clear relationship between the monthly average GHX LFTs and the system COPs because of the narrow variation in average GHX LFTs and the different room temperatures among

the test homes. However, in an individual home in which the room temperature was maintained nearly constant, detailed minutely measurements clearly show the impact of GHX LFT on the system COP. As shown in Fig. 9, GHX LFT decreased during each heating operation cycle, resulting in a decrease in the system COP.

Further analysis of the measured data reveals that the system COP is affected not only by the room temperature and the GHX LFT, but also by the thermostat control of the GSHP systems. As shown in Fig. 10a, the thermostat in unit 8 was set to run the GSHP system only at certain time periods during the day. Consequently, whenever the GSHP system turned on, it had to warm up the home from a low temperature (due to temperature drift when the system was off). In contrast, the GSHP system in unit 2 (Fig. 10b) was set to run all day long and maintained the room temperature within a narrow range. As a result, the GSHP system in unit 8 had a higher average COP than the system in unit 2, although the GHX LFT in unit 8 was lower than that in unit 2 and the average room temperatures (when the GSHP systems were in operation) in the two units were almost the same. As a result of the shorter operating hours (73 hours in unit 8 vs. 132 hours in unit 2), the GSHP system in unit 8 also consumed less power than the system in unit 2 (see Fig. 12).

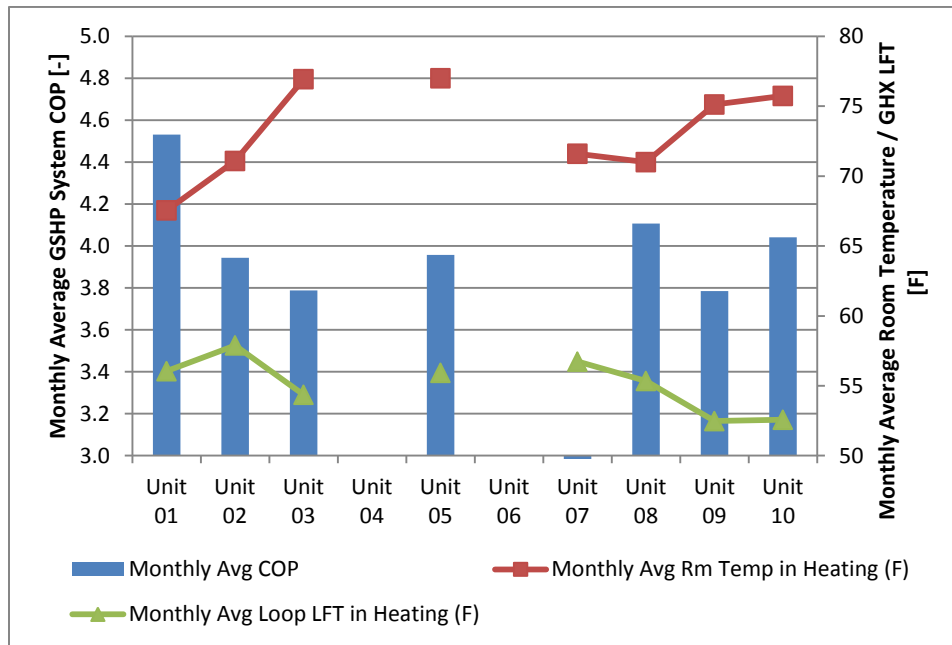


Fig. 8. Monthly average COPs of the GSHP systems and the associated average room temperatures and GHX LFTs at each of the test homes in February 2012.

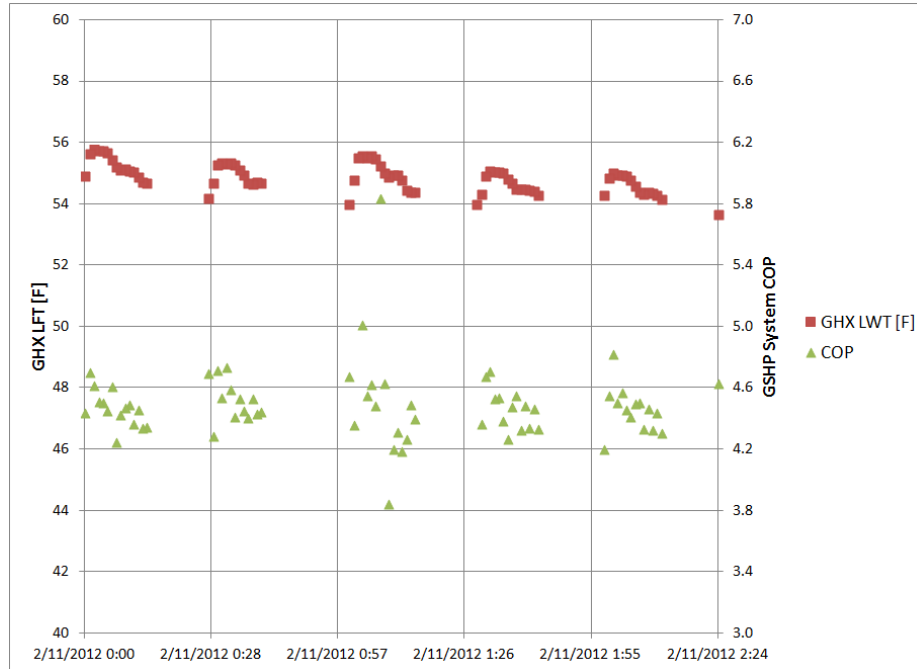
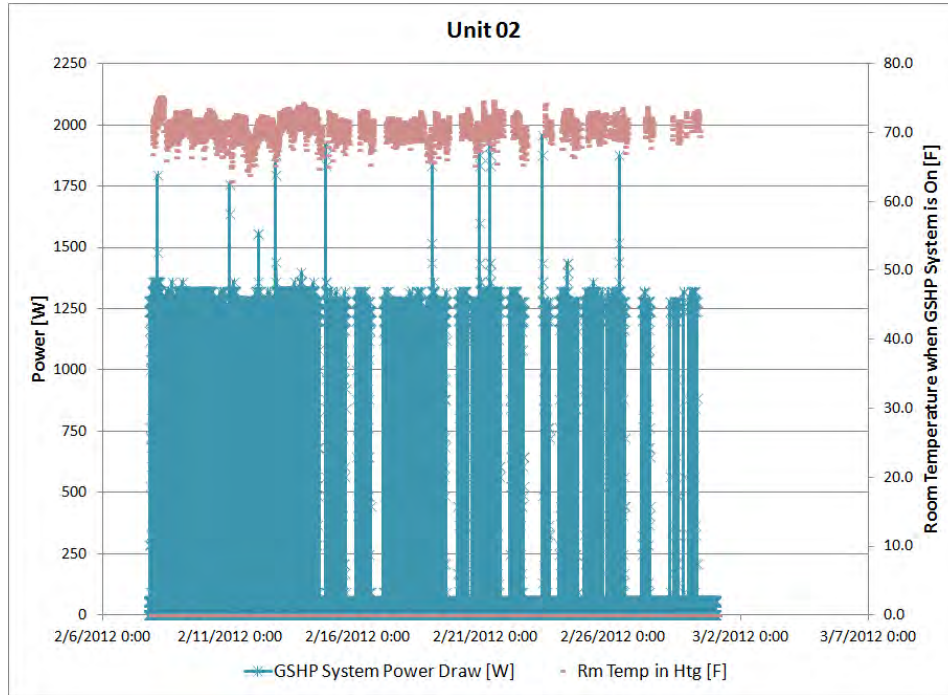


Fig. 9. A close-up look at the LFT from the GHX and the coincident instantaneous values of GSHP system COP.



(a) Unit 8 (intermittent operation)



(b) Unit 2 (continuous operation)

Fig. 10. GSHP system power draw and coincident room temperature in units 2 and 8.

4.1.3 Electric Power Consumption

Figure 11 shows the monthly total power consumption of the GSHP systems at the ten test homes (including the heat pump unit compressors and fans, the circulation pump, and the desuperheater pump). The total GSHP system power consumption varied significantly during the heating season, although the locations, sizes, and construction of the homes are almost identical. The total GSHP system power consumption in units 3 and 9 (over 400 kWh in December 2011) was more than double that in units 1, 2, and 8 (under 200 kWh in December 2011).

Further analysis indicated it was the difference in room temperatures maintained in the test homes that resulted in the large discrepancies in total GSHP system power consumption. Figure 12 demonstrates a clear relationship between the average room temperature and the total power consumption of the GSHP systems: the higher the monthly average room temperature (when heating is on), the higher the power consumption. The lowest GSHP system power consumption (157 kWh) in February 2012 occurred in unit 1, in which the room temperature was maintained at the lowest level among all the test homes (67.6°F). At the opposite extreme, unit 3 maintained the highest room temperature (77.9°F) and, as a result, its GSHP system consumed the most power (380 kWh) among all the test homes. The 10.3°F lower average room temperature in unit 1 resulted in a 58.7% reduction in total GSHP system power consumption compared with unit 3.

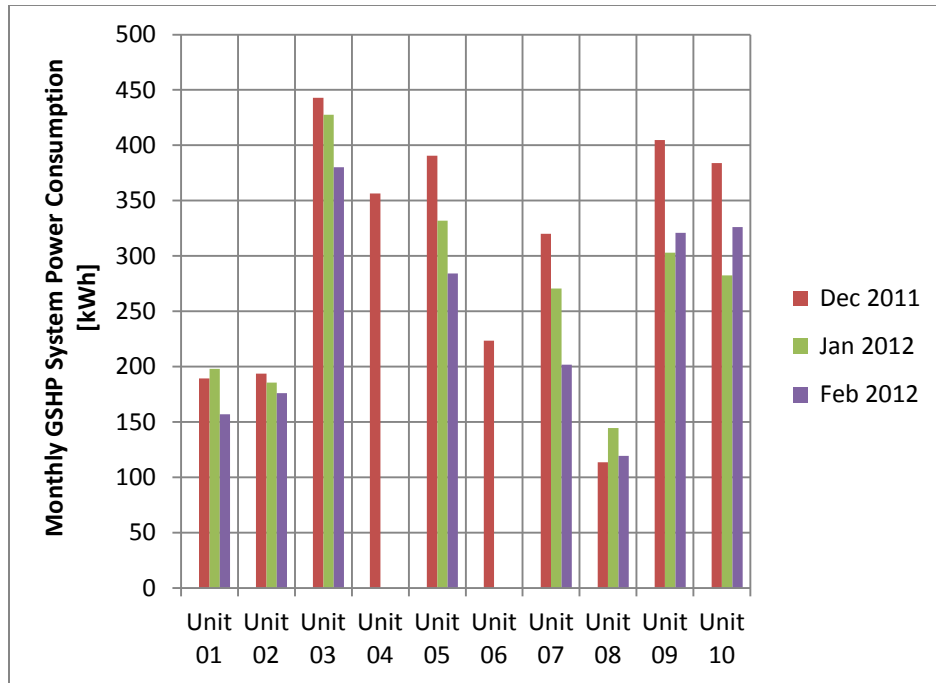


Fig. 11. Monthly total GSHP system power consumption during heating season at the ten test homes.

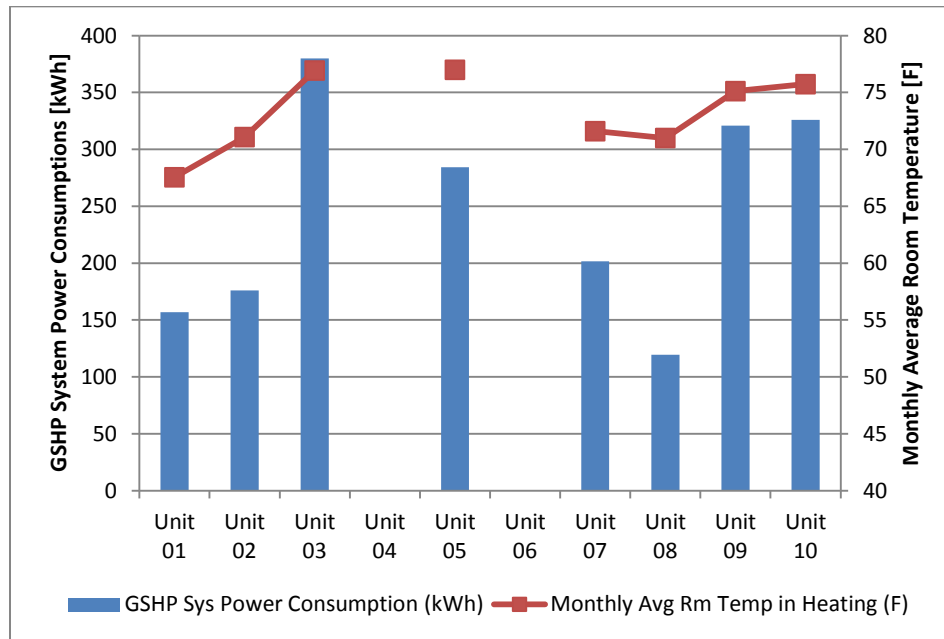


Fig. 12. Monthly average room temperature and the corresponding total GSHP system power consumption in February 2012 at the test homes.

4.1.4 Peak Electricity Demand

The monthly peak electricity demand of the GSHP systems (those that had valid power measurements) varied from 1.8 to 2.2 kW in the heating season (Fig. 13). These numbers are consistent with the power draw data provided in the manufacturer's catalog for the heat pump running in full-load mode and at the

same entering fluid temperature (see Appendix A), if the pumping power for the circulation pump and the desuperheater pump (about 100 W each, on average) are taken into account. The discrepancies in the peak electricity demand are thought to be due to operation of the variable-speed circulation pumps of the GSHP systems, which were controlled to maintain a constant differential temperature across the GHX.

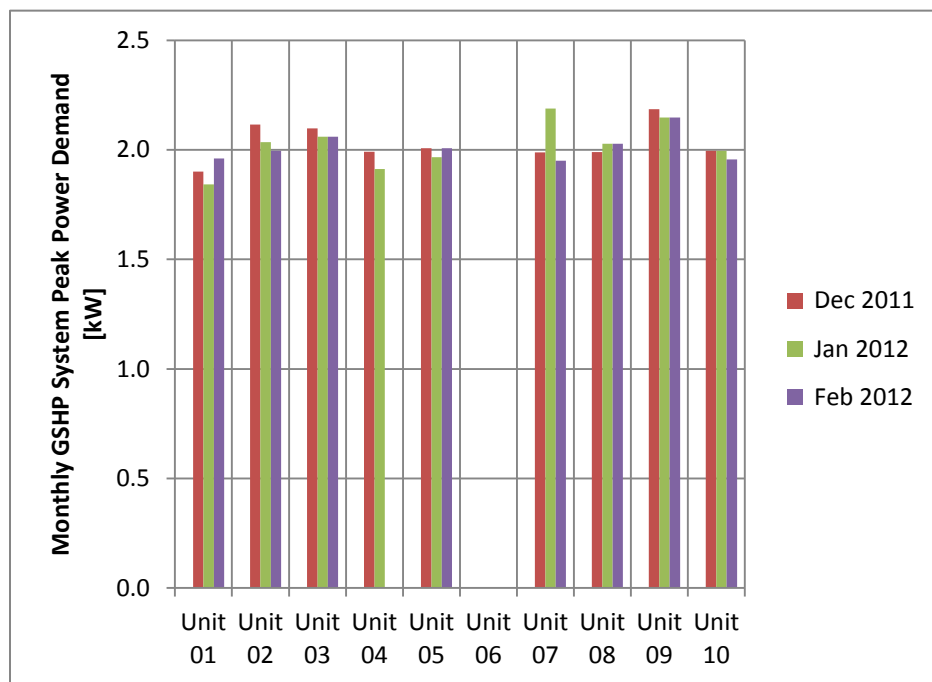


Fig. 13. Monthly peak electric demand of the GSHP systems in heating season.

4.2 COOLING SEASON

The hourly ambient dry-bulb temperature measured at the Will Rogers International Airport in Oklahoma City from June through August 2012 is plotted in Fig. 14. The temperature data are from NOAA. The average ambient dry-bulb temperature was 83.5°F and fluctuated from 54.7 to 111.0°F during the cooling season. Oklahoma City had 18 straight days where temperatures reached 100° or greater, including three days in a row that were 112°, exacerbating wildfires and drought in the state. The only heat wave in Oklahoma history that compares to the August 2012 heat wave occurred during the great Dust Bowl summer of 1936, the hottest summer in U.S. history. Oklahoma City experienced a record streak of 22 straight days with a temperature of 100° or hotter that year.

The data acquisition system in unit 2, which uses the original GHX and was one of the reference cases in this study, was disconnected before the cooling season began, by the request of the home owner. As mentioned earlier, the flow rate measurements in units 6 and 7 were not valid, and the flow rate measurement in unit 4 also became invalid beginning in July 2012. As a result, the system EERs of the GSHP systems in these three units could not be determined for all the months in the cooling season. In addition, the GSHP system in unit 9, which previously had used only a new co-axial GHX, used both the original GHX and the new co-axial GHX beginning in August 2012. The change was due to the high LFT from the new co-axial GHX, which was believed to be due to higher than expected cooling loads in this home.

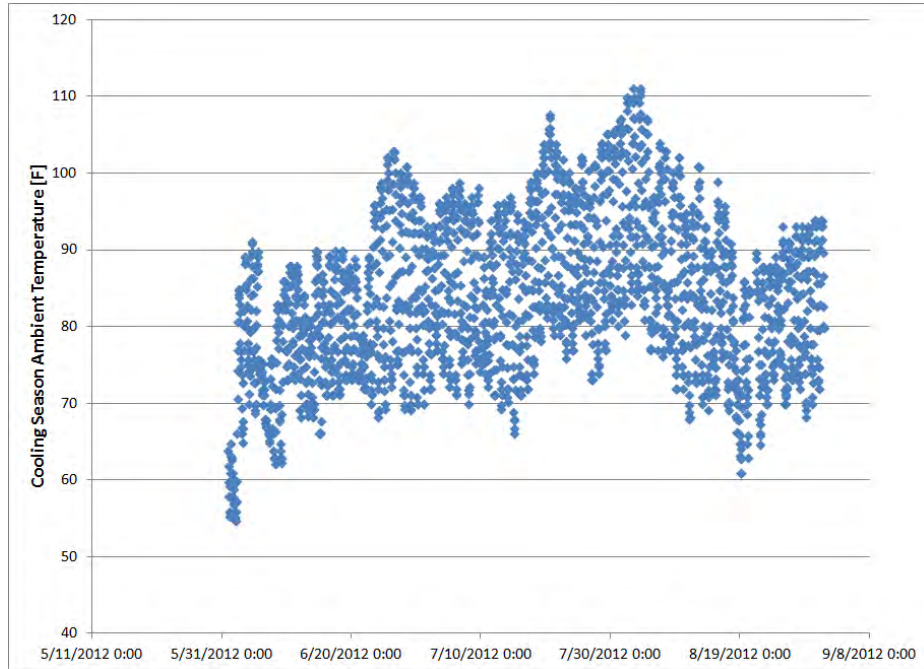


Fig. 14. Ambient dry-bulb temperature in the cooling season measured at Will Rogers International Airport in Oklahoma City.

4.2.1 Operating Conditions

The cooling efficiency of the GSHP systems was also affected by the room (return air) temperature and the GHX LFT. As shown in Fig. 15, the monthly average room temperatures in all of the test homes during the cooling season were similar—approximately 73°F with a deviation of less than 3°F.

The monthly average and maximum GHX LFTs in the test homes varied more widely in the summer than in the winter. Figure 16 shows that, although the average GHX LFT was nearly constant at around 76°F in unit 10 during the three summer months, it reached 100°F in July in unit 9 with a maximum temperature at 109.4°F (and was even higher in August, resulting in an early termination of the test). The monthly average GHX LFT at all of the other test homes except unit 10 increased over the first two months and leveled or dropped slightly in August. The monthly average GHX LFT in units 4 and 9 had the largest increase (about 10°F) in the first two months among all the test homes, and the temperature increase in the other homes was less than 5°F. The monthly maximum GHX LFT in units 4 and 9 exceeded 95°F, which indicated that the GHXs in these two units were undersized.

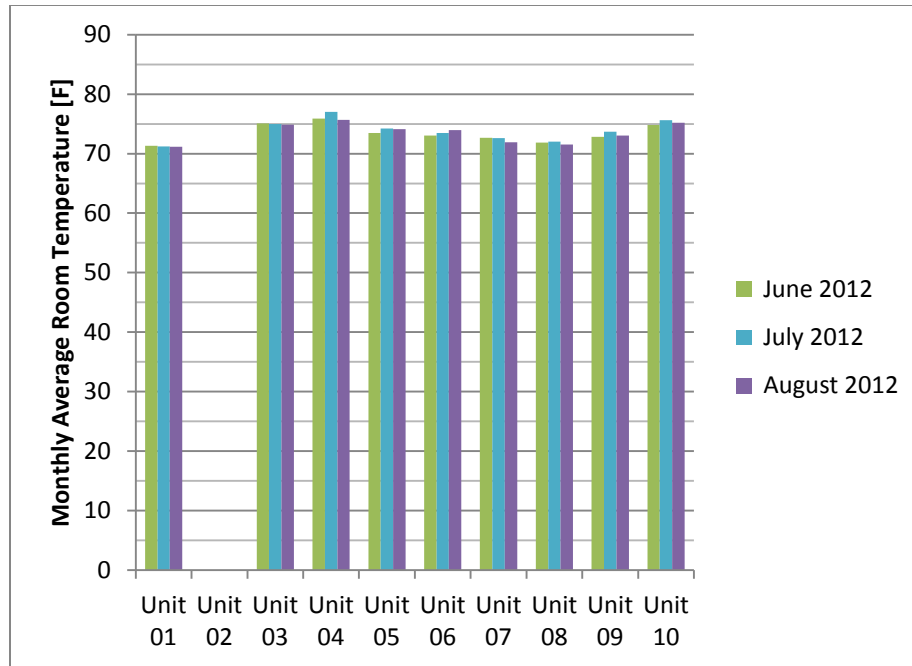
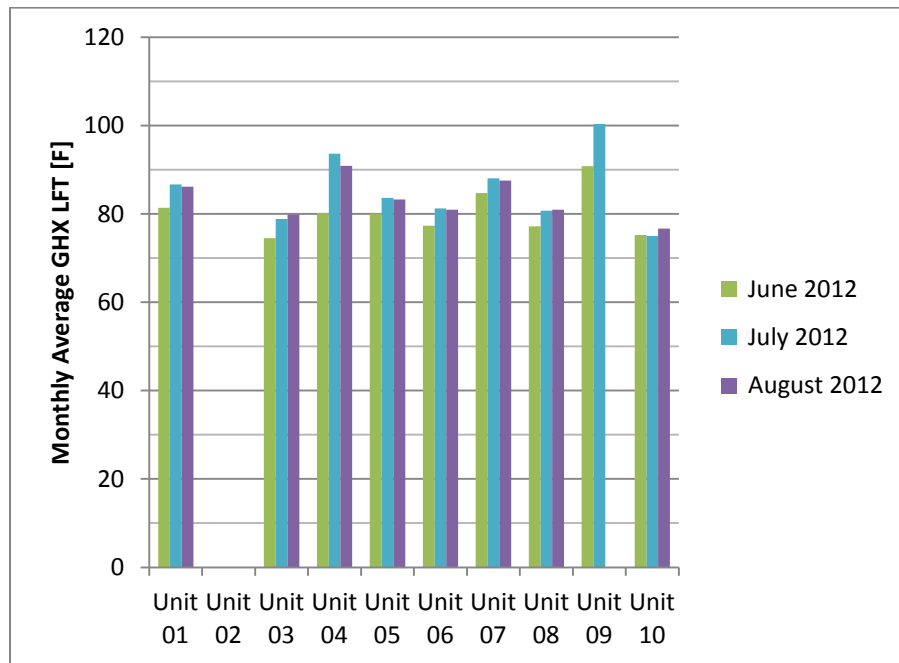
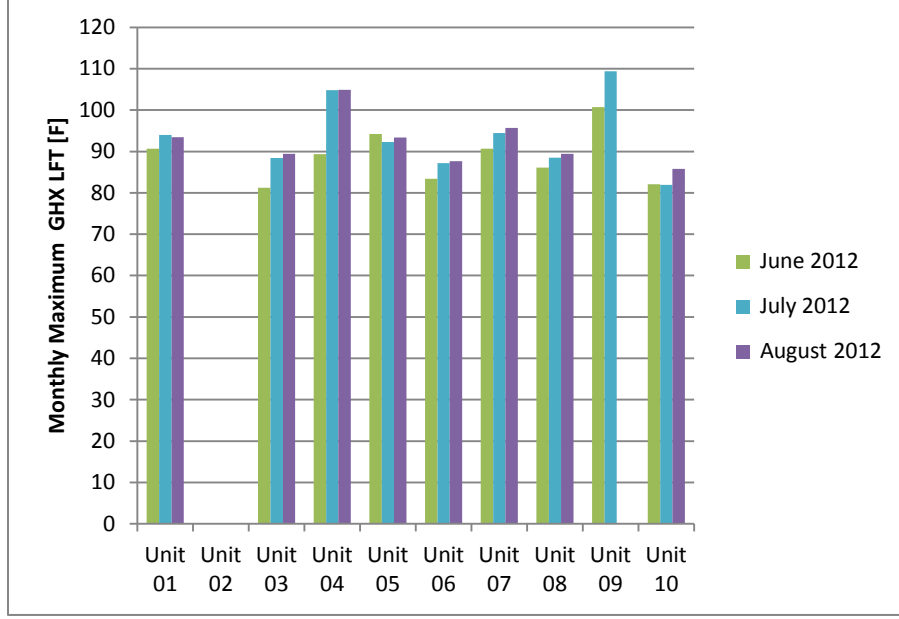


Fig. 15. Monthly average room temperature maintained by the GSHP system in the test homes (measured when the GSHP systems were operating in cooling mode).



(a) Monthly average LFT from the GHX



(b) Monthly maximum LFT from the GHX

Fig. 16. Monthly average and maximum LFT from the GHX of each GSHP system (measured when the GSHP systems were operating in cooling mode).

4.2.2 System EER

Seven of the ten test homes collected enough data to calculate the monthly GSHP system EER. The system EER at each minute can be calculated with in Eq. 6. Since the desuperheater was used for preheating the domestic water and does not contribute to the cooling operation, the power draw of the circulator of the desuperheater (P_{DSH_Pump}) is extracted from the total GSHP system power draw in the calculation of EER.

$$EER = \frac{QC}{P_{HP} - P_{DSH_Pump}} = \frac{Q_{GL} + Q_{DSH} - P_{HP} \times 3.413}{P_{HP} - P_{DSH_Pump}} \quad (6)$$

Due to the limited available channels in the data acquisition system, Q_{DSH} was not directly measured in this study. It is estimated based on the catalog data of the heat pump manufacturer. As can be seen in Appendix A, Q_{DSH} is about 10% of QC when the heat pump entering fluid temperature is around 80°F, which is the monthly average GHX LFT at most of the test homes during cooling season as shown in Fig. 16. In addition, the measured data shows that P_{DSH_Pump} (around 100 W) is about 5% of P_{HP} (around 2,000 W). Based on this information, Eq. 7 is derived from Eq. 6 and used to calculate the system EER at each minute.

$$EER = \frac{(Q_{GL} - P_{HP} \times 3.413) / (1 - 0.1)}{(1 - 0.05)P_{HP}} = 1.17 \frac{(Q_{GL} - P_{HP} \times 3.413)}{P_{HP}} \quad (7)$$

The monthly system EER (\overline{EER}) is calculated with Eq. 2 as discussed previously. As can be seen in Fig. 17, the monthly system EERs in the seven homes ranged from 11.4 to 18.7 at the beginning of the cooling season and decreased in the following months. The percentage of decrease in the monthly average EER

ranged from 5% (unit 5) to 18% (unit 9³). Except in units 1 and 9, the system EERs in other units were in range from 14.7-18.7 during the cooling season. These numbers are slightly lower than the EER (16.8 at full load condition and 19.5 at part load condition) provided in the manufacturer's catalog when the entering fluid temperature is at 80°F (see Appendix A). The difference is thought due to the different pump power and fan power than that used in generating the catalog data. The room temperature, which is lower than rating condition (80°F) is another reason for the lower EERs.

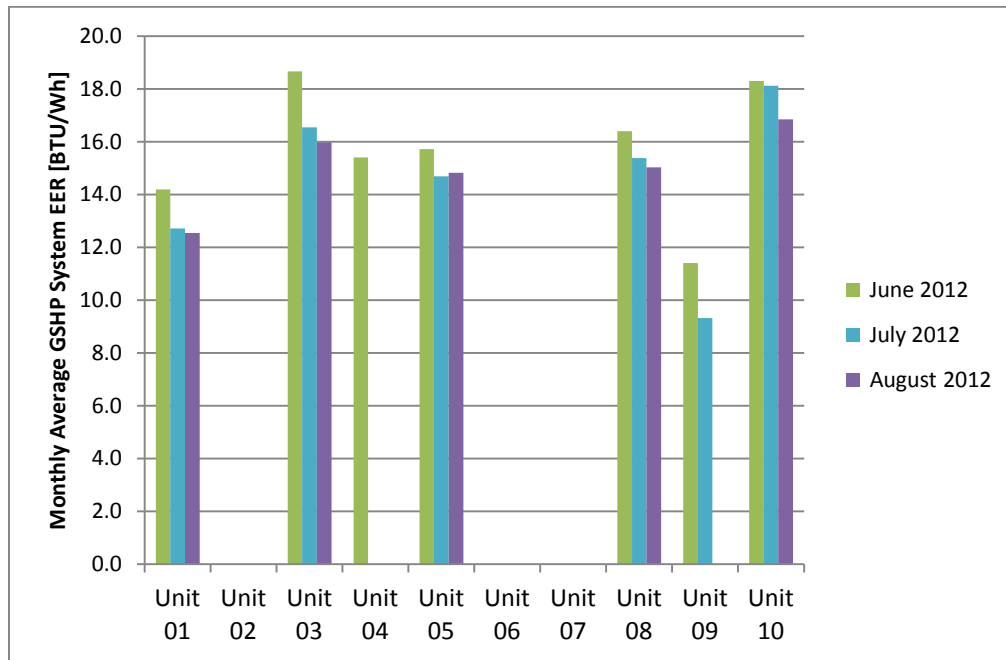


Fig. 17. Monthly average EER of the GSHP systems

Since the room temperatures in these homes were maintained within a similar range during the cooling season (as shown in Fig. 15), the difference in the EER values is mainly the result of different GHX LFTs at each home. Figure 18 plots the GSHP system EER, room temperature, and GHX LFT in July 2012. It is apparent that the low EER values are associated with high GHX LFTs: unit 10 had the lowest average GHX LFT (75°F) and the highest average EER (18.1), whereas unit 9 had the highest average GHX LFT (100.4°F) and the lowest average EER (9.3). Given that the typical maximum GHX design temperature for residential applications is 95°F, the 109.4°F maximum GHX LFT for unit 9 indicated that its GHX was undersized for the given building loads; thus the low EER is not representative of a properly designed GSHP system.

These results revealed two important issues in evaluating the performance of a GSHP system: (1) the system performance should be measured during a time period long enough to capture the full spectrum of variations during the entire heating and cooling season, and (2) the room temperature and the ground loop temperature need to be measured to determine whether the GSHP system is sized properly for the given building loads.

³ The monthly average EER dropped 18% in just two months in unit 9. Further analysis indicated that unit 9 had a much higher cooling load than it was designed for, exceeding the 2 ton capacity of the installed GSHP system.

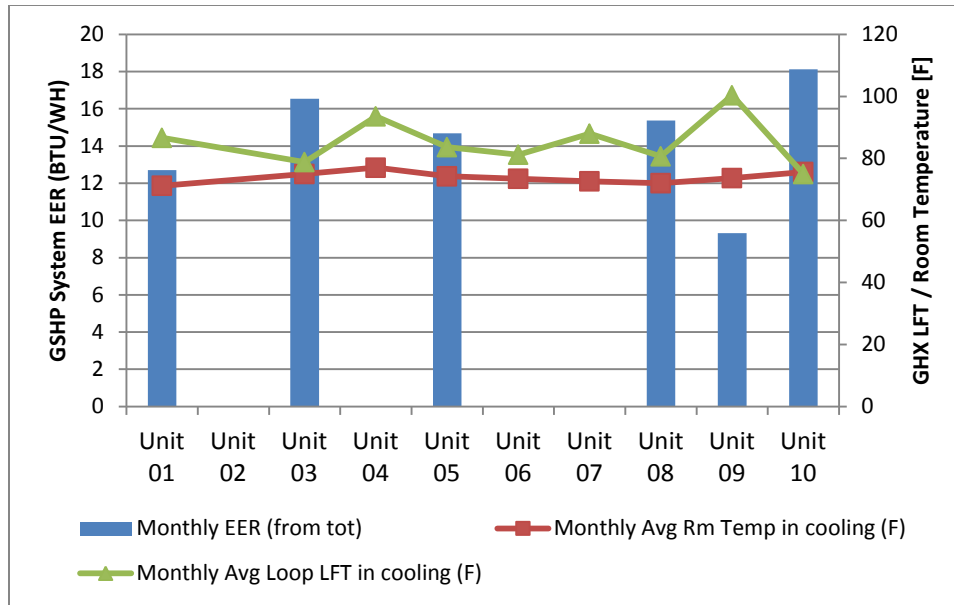


Fig. 18. Monthly average room temperatures and GHX LFTs and resulting monthly average GSHP system EERs in July 2012.

4.2.3 Electric Power Consumption

Figure 19 charts the monthly total GSHP system power consumption at each of the nearly identical test homes (including the compressor and fan of the heat pump unit, the circulation pump, and the desuperheater pump). As was observed in the heating season, the GSHP system power consumption varied widely during the cooling season, although the average room temperature in these homes was maintained at about the same level. It can be seen clearly in Fig. 20 that the large variation in GSHP system power consumption is the result of the different GHX LFTs in the systems.

Figure 20 shows that the GSHP system power consumption of unit 9 was more than four times that of unit 10. Since the EER for the unit 9 GSHP system is about half that of the unit 10 system, the fourfold difference in total energy consumption is due not only to the difference in EER but also to the different cooling loads, and the resulting operating hours, of the two systems. The minute-level data shown in Fig. 21a and b support this analysis, showing that the system in unit 9 ran at full-load mode much more frequently than the system in unit 10.

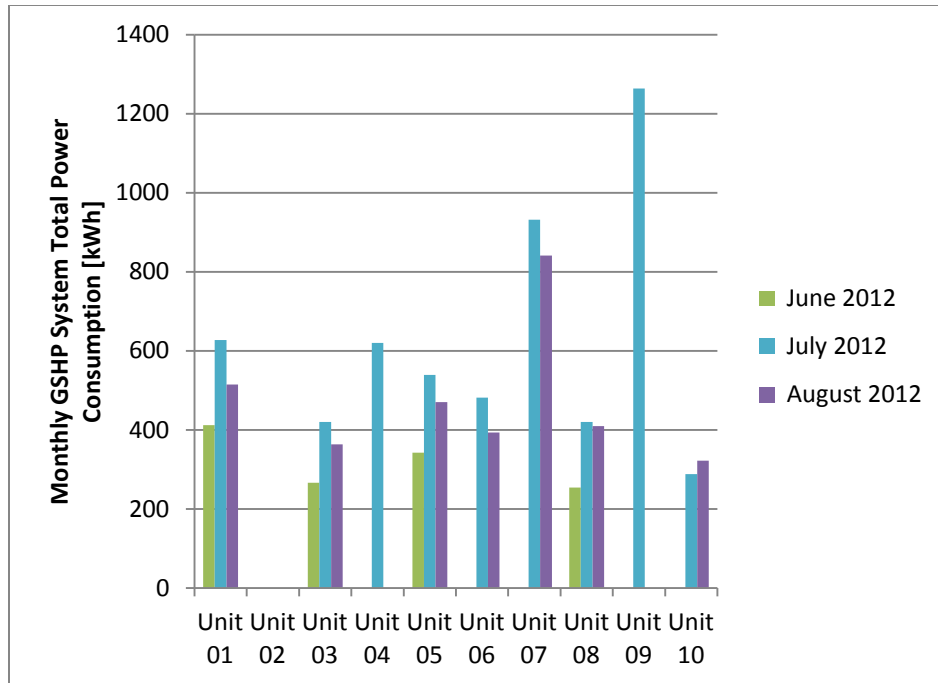


Fig. 19. Monthly total GSHP system power consumption of the test homes in cooling season.

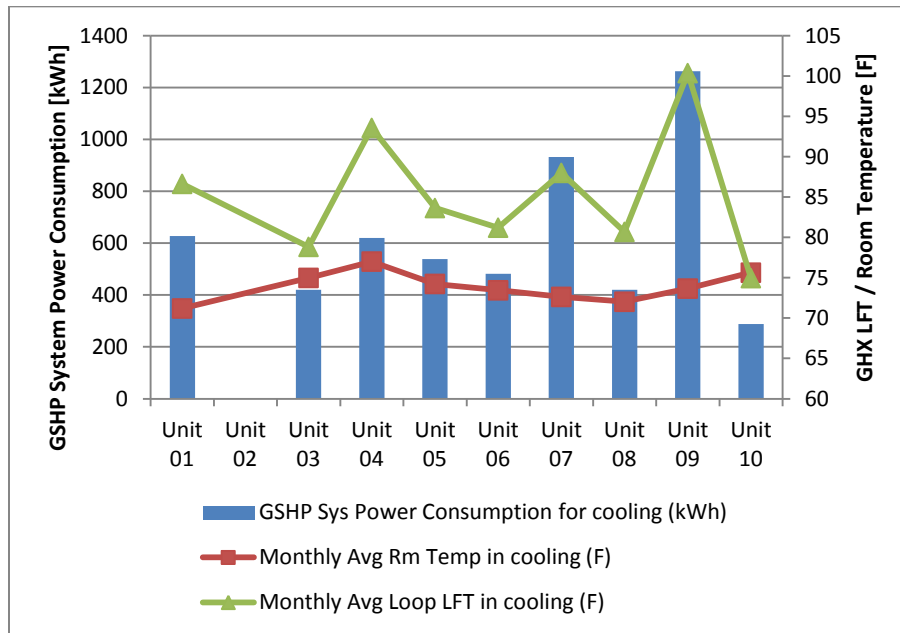
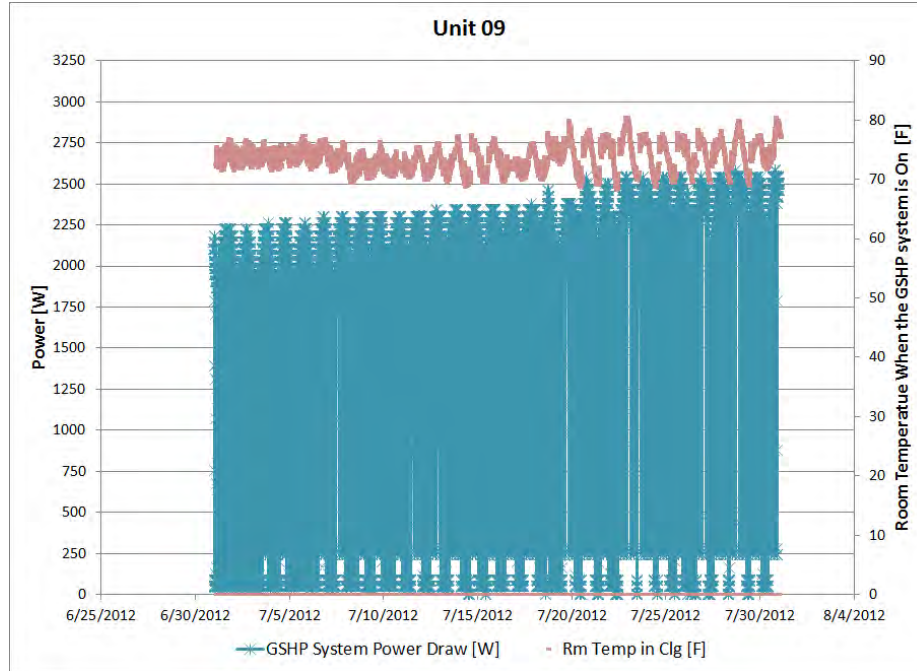
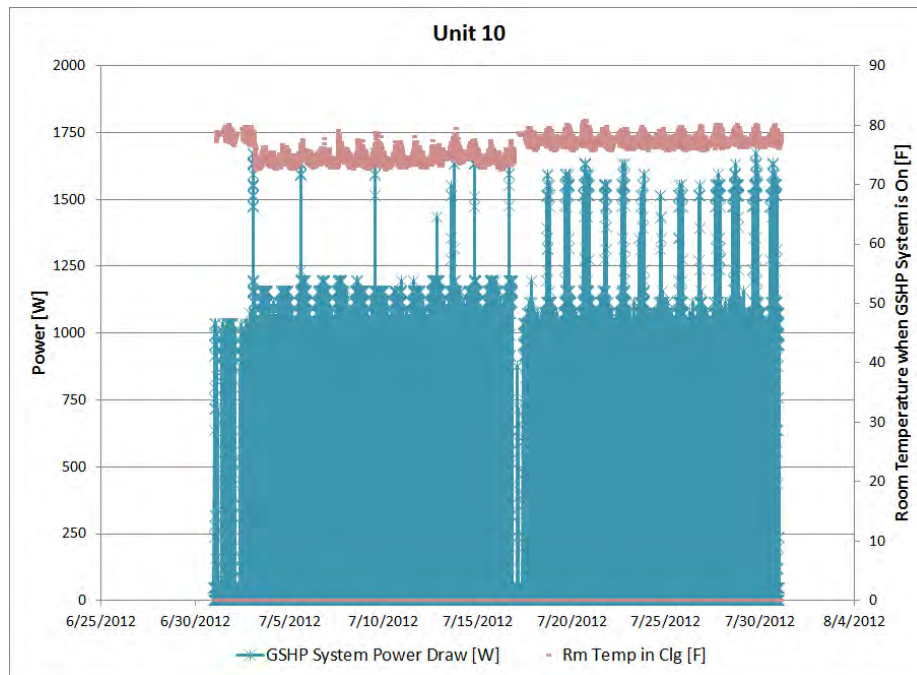


Fig. 20. Monthly total GSHP system power consumption and coincident average room temperature and GHX LFT in July 2012.



(a) Unit 9 (with higher than expected cooling loads)



(b) Unit 10 (with expected cooling loads)

Fig. 21. GSHP system power draw and coincident room temperature in units 9 and 10 in July 2012.

4.2.4 Peak Electricity Demand

The monthly peak electricity demands of the eight GSHP systems with valid electric power measurements during the cooling season are shown in Fig. 22. They varied from 1.6 to 2.6 kW during the cooling

season. These numbers are consistent with the power draw data in the heat pump manufacturer's catalog for the same operating conditions and at full-load mode, after accounting for the pumping power for the circulation pump and the desuperheater pump (usually less than 200 W in total). The high peak electricity demand in unit 9 was believed to be due to the very high GHX LFT, which resulted in a high power draw from not only the heat pump compressor but also the variable-speed circulation pump. The circulation pump was ramped up to deliver a higher flow rate to maintain the predefined constant differential temperature across the GHX.

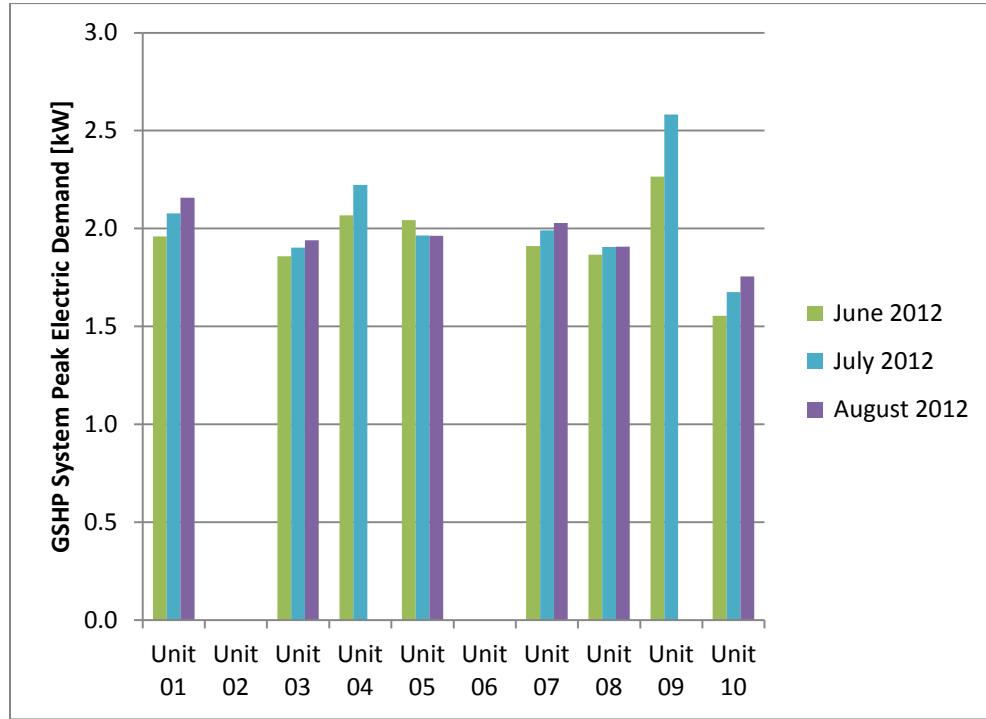


Fig. 22. Monthly peak electricity demand of the GSHP systems in cooling season (in homes where some data were missing during the month, the data shown in the chart are the maximum values of the available power draw data during the month).

5. ANALYSIS OF DRILLING DEPTH REDUCTION POTENTIAL OF THE NEW GHXS

One of the main goals of this study is to determine whether the new GHXs can reduce the required drilling depth while retaining the same GSHP system performance. The required depth for a given GHX depends on multiple factors, including the loading profile imposed on it, the ground heat transfer characteristics, and the borehole thermal resistance. For a given building at a given location, the only factor determining the required drilling depth is the borehole thermal resistance of the GHX.

At the beginning of this study, the industrial partners (Ewbank and Associates) conducted in-situ tests to determine the effective ground thermal conductivity at each test home. The measured data from the insitu tests were further analyzed to estimate the borehole thermal resistance of six new GHXs (Beier 2012). The estimated borehole thermal resistances of the six new GHXs are presented in Fig. 23, from low to high values.

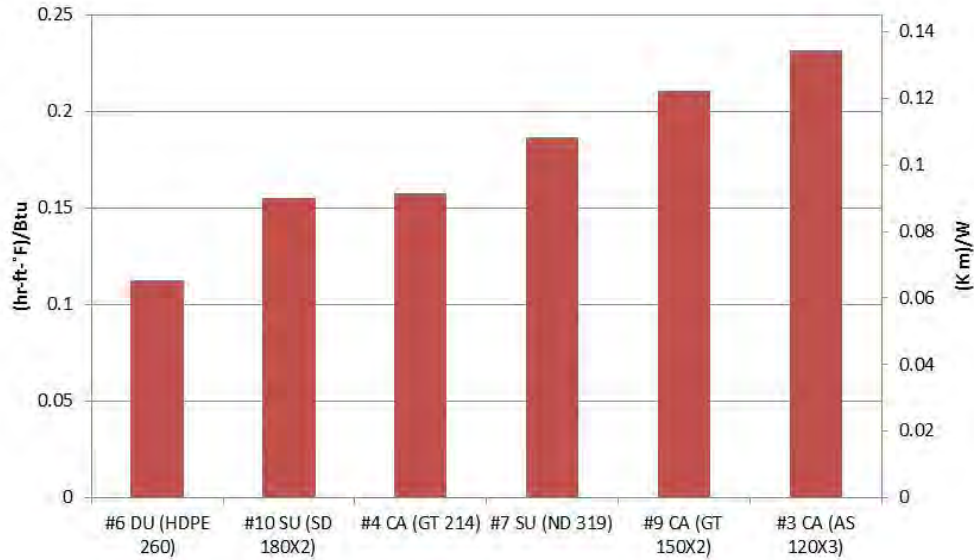


Fig. 23. Borehole thermal resistance of six new GHXs estimated from the in-situ test data.

To assess how much the new GHXs can reduce the required drilling depth, a computer model of one of the test homes—unit 3—was developed with eQUEST software, which has reliable simulation capability for GSHP systems (Liu 2008). Figure 24 shows a photograph of unit 3 and a 3-dimensional rendering of the computer model of the house. The model predicted annual GSHP system power consumption was very close to the measured data in unit 3 with less than 10% difference. The discrepancy between the model predicted heating and cooling output and the corresponding measured data was less than 20%, as shown in Fig. 25. A perfect match between the model prediction and measured data is not necessary in this study as long as same building loads are used in the simulations of the various GHXs.

With the calibrated eQUEST model, a few simulations were conducted to determine the required borehole depth of the new GHXs for maintaining the maximum GHX LFT under the same level (around 93°F) in response to the identical building loads and the same ground thermal conductivity and undisturbed ground temperature. The new GHXs are modeled with their actual borehole diameters and the borehole thermal resistance values estimated from the in-situ tests (as shown in Fig. 23).

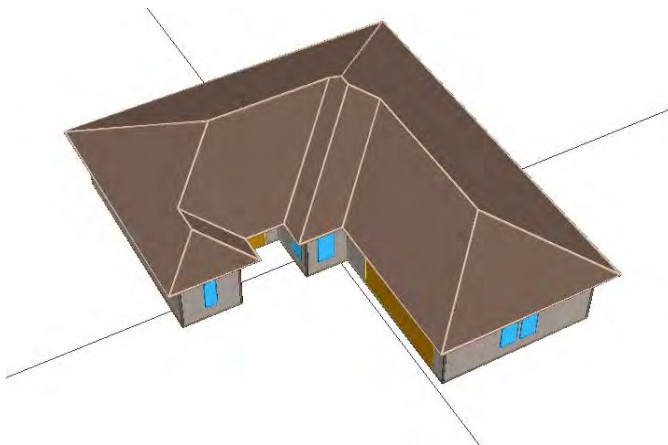
Table 2 summarizes key parameters of the simulation and the predicted borehole depth reduction resulting from three new GHXs, which represent three different levels of borehole thermal resistance shown in Fig. 23. As shown in Table 2, the double U-tube GHX can reduce the required borehole depth by 35% compared with the conventional single U-tube GHX. The single U-tube GHX with small borehole diameter and top-only grouting can reduce the required borehole depth by 30%. The Geothex co-axial GHX with Barotherm Max grout (installed in unit 4) has similar borehole resistance to the single U-tube GHX with small borehole diameter and so can also reduce the required drilling depth by 30% (not listed in Table 2). The Geothex co-axial GHX with Barotherm Gold grout (installed in unit 9) can reduce the required borehole depth by 21%.

For a given reduction in borehole thermal resistance, the resulting reduction in required borehole depth depends on the ground thermal conductivity value. The required borehole depths of the conventional single U-tube GHX and the double U-tube GHX for maintaining the same maximum GHX LFT are determined with the simulations and the results are presented in Fig. 26. As shown in this figure, the reduction in required borehole depth increases to 39% if the ground thermal conductivity value is a bit

higher [2.2 Btu/(hr-ft-°F)] and it decreases to 29% at a place with poor ground thermal conductivity [1.2 Btu/(hr-ft-°F)].

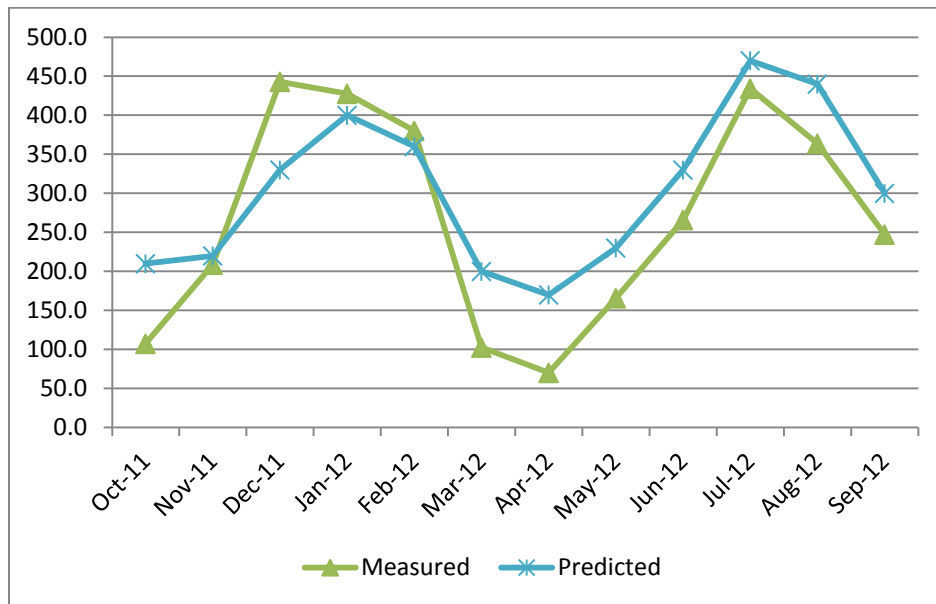


(a) A bird's-eye view photograph of unit 3

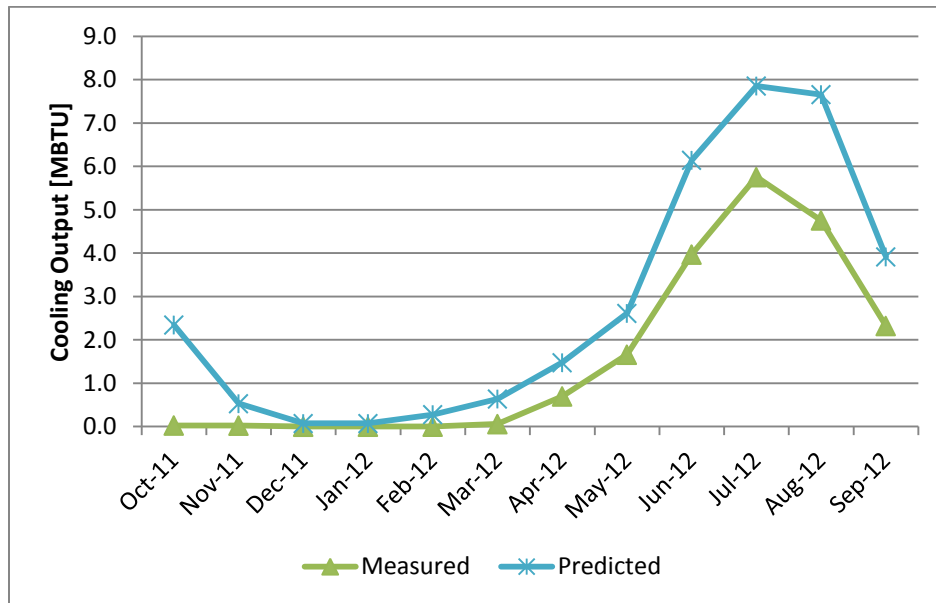


(b) A 3-dimensional rendering of the eQUEST model of unit 3

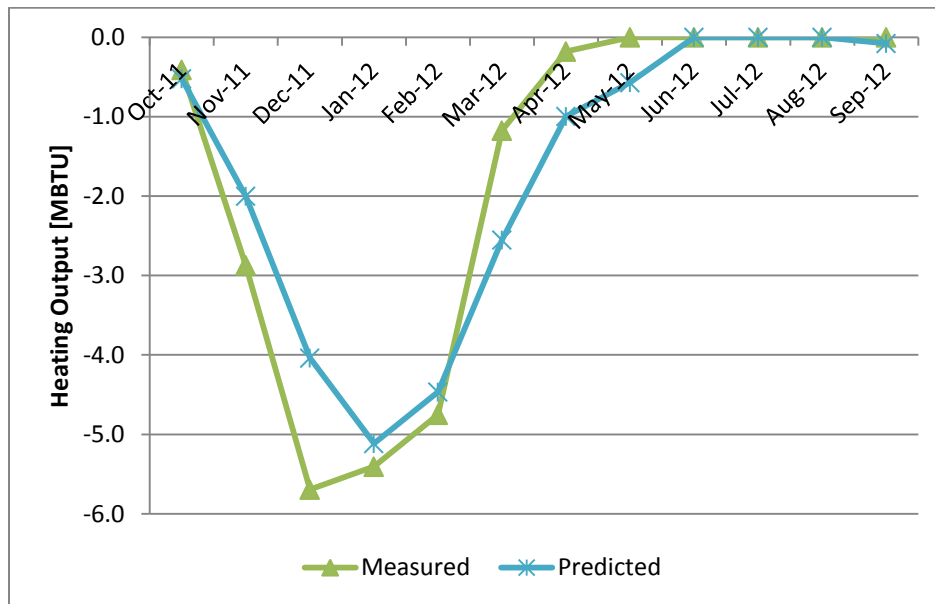
Fig. 24. The eQUEST model of one of the test homes.



(a) Comparison of annual GSHP system power consumption between predicted and measured data



(b) Comparison of annual cooling output of the GSHP system between predicted and measured data



(c) Comparison of annual heating output of the GSHP system between predicted and measured data

Fig. 25. Comparison between model predictions and measured data.

Table 2. Reduction of borehole depth resulting from the new GHXs

Undisturbed soil temperature, °F (°C)		63.0 (17.2)		
Soil thermal conductivity, Btu/(hr-ft-°F); W/(K m)		1.85 (3.2)		
GHX type	Single U-tube	Geothex®	Single U-tube	Double U-tube
Grout type	Bentonite	Barotherm® Gold	0.43 (0.74) [Top 50 ft of borehole]	
Grout thermal conductivity, Btu/(hr-ft-°F); W/(K m)	0.43 (0.74)	0.83 (1.44)	0.43 (0.74)	0.82 (1.42)
Borehole diameter, in. (mm)	5.25 (133)	4.75 (121)	2.75 (70)	5.25 (133)
Borehole resistance, (hr-ft-°F)/Btu; (K-m)/W	0.364 (0.21)	0.22 (0.127)	0.155 (0.09)	0.113 (0.065)
Borehole depth ft (m)	400 (121.9)	315 (96.0)	280 (85.3)	257 (78.3)
Max loop LFT °F (°C)	93.0 (33.9)	93.2 (34.0)	93.0 (33.9)	93.0 (33.9)
Percent reduction in borehole depth (%)		21%	30%	36%

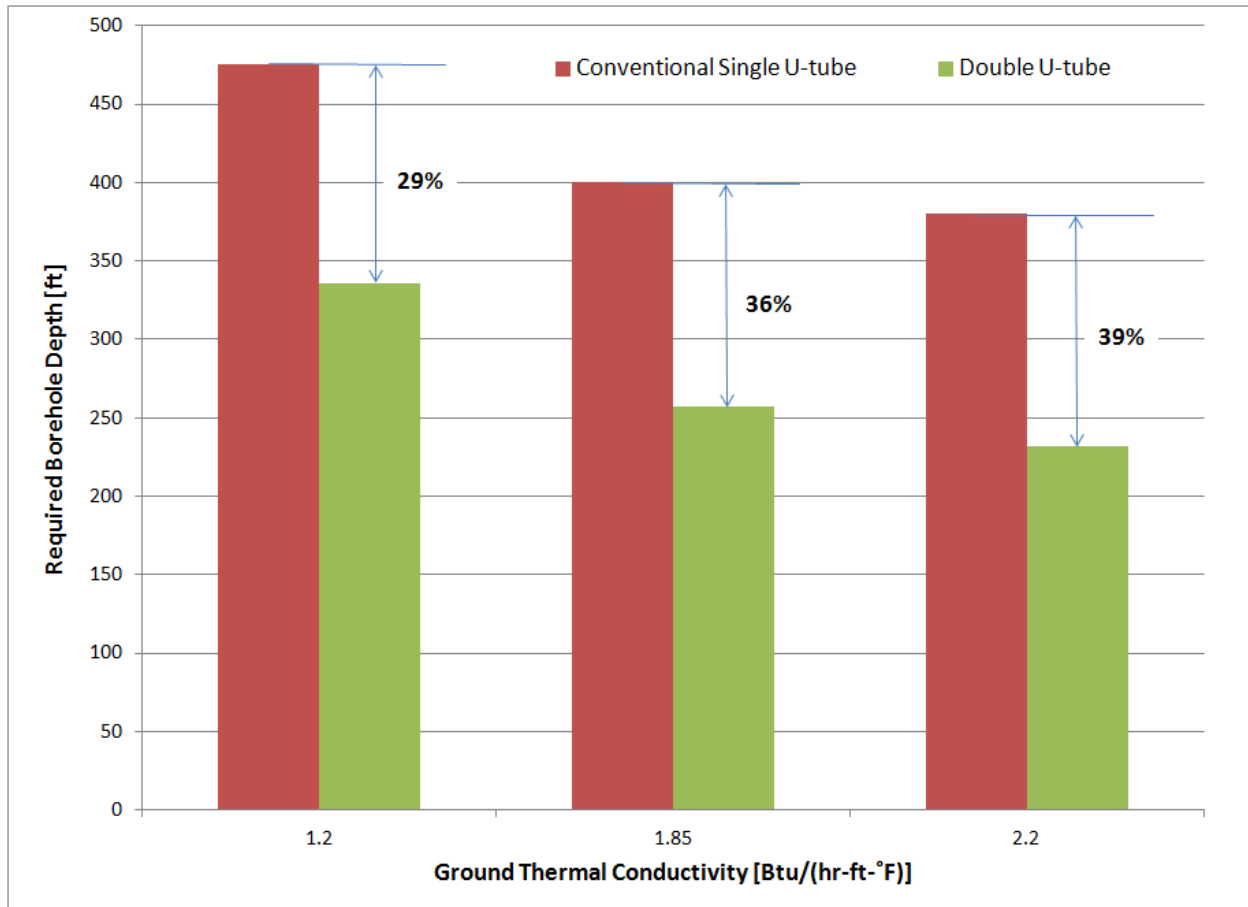


Fig. 26. Comparison of the reduction of the required borehole depth with different ground thermal conductivities.

6. CONCLUSIONS

6.1 GSHP SYSTEM PERFORMANCE

The measured performance data show that the GSHP systems maintained the room temperature at the setpoint specified by individual homeowners except in unit 9, where the building cooling load is thought to have exceeded the capacity of the 2 ton GSHP system.

The GSHP system COP in heating season was close to each other (3.8 to 4.5) among the test homes and the differences in COP were attributable to individual homeowners' thermostat settings; the system EER in cooling season varied widely from 9.3 to 18.7 among the test homes. Except in units 1 and 9, where the GHX was undersized, the system EERs were above 14.7 during the cooling season. The discrepancy in system EERs was a result of the wide variation of the leaving fluid temperature from the GHXs during the cooling season.

The monthly peak electricity demand of the tested 2-ton GSHP systems varied from 1.8 to 2.2 kW during the heating season and it varied from 1.6 to 2.6 kW during the cooling season. The high summer peak electricity demand in unit 9 was believed to be due to the very high GHX LFT, which resulted in a high power draw from not only the heat pump compressor but also the variable-speed circulation pump.

The energy consumption of the tested GSHP systems varied significantly among the nearly identical test homes and were affected by many factors, including room temperature (especially in winter, when the room temperature significantly affected the heating loads of the test homes), GHX LFTs, and thermostat control. It is necessary to monitor the GSHP system for an entire heating and cooling season to capture the full spectrum of the performance variation. A standardized data collection and analysis procedure for evaluating the performance of a GSHP system does not exist currently and it is highly desirable.

6.2 BOREHOLE DEPTH REDUCTION FROM THE NEW GHXS

Both the field tests and the computer simulations concurred that the double U-tube GHX requires 36% less borehole depth compared with a conventional single U-tube GHX while retaining same performance at given building load and ground condition [with a 1.85 Btu/(hr-ft-°F) thermal conductivity]. Other new GHXs being tested also show the potential to reduce the required borehole depth, although the reductions are smaller (20-30%). A larger reduction in required borehole depth can be expected at locations where the ground thermal conductivity value is higher.

7. REFERENCES

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- Beier, R. 2012. *In-Situ Test Thermal Response Tests: Interpretations: OG&E Ground Source Heat Exchange Study*, International Ground Source Heat Pump Association.

**APPENDIX A. CATALOG DATA FOR THE HEAT PUMP UNIT
USED IN THIS STUDY**

APPENDIX A. CATALOG DATA FOR THE HEAT PUMP UNIT USED IN THIS STUDY

ClimateMaster Tranquility® 27 Model 026 — Full Load Mode Performance Data

(http://www.climatemaster.com/share/Res_All_Products_CLM/Section_3_TT27.pdf)

EWT °F	GPM	WPD		Cooling - EAT 80/67°F							Heating - EAT 70°F						
		PSI	FT	Airflow CFM	TC	SC	kW	HR	EER	HW	Airflow CFM	HC	kW	HE	LAT	COP	HW
20	8.0	5.6	12.9	Operation not recommended							820	15.0	1.47	10.2	86.9	3.00	1.7
	8.0	5.6	12.9								950	15.3	1.41	10.6	84.9	3.19	1.7
30	4.0	1.5	3.5	730	30.2	17.9	0.97	33.4	31.0	0.8	820	17.8	1.53	12.7	90.1	3.41	2.0
	4.0	1.5	3.5	850	30.9	19.6	1.02	34.3	30.4	0.8	950	18.1	1.46	13.2	87.7	3.63	2.0
	6.0	3.1	7.2	730	30.3	17.9	0.93	33.4	32.7	0.5	820	18.6	1.54	13.5	91.0	3.53	2.1
	6.0	3.1	7.2	850	31.1	19.6	0.97	34.4	32.1	0.6	950	19.0	1.48	14.0	88.5	3.76	2.1
	8.0	5.1	11.7	730	30.5	17.9	0.91	33.5	33.7	0.5	820	19.1	1.55	13.9	91.5	3.59	2.1
	8.0	5.1	11.7	850	31.2	19.6	0.95	34.5	33.1	0.5	950	19.4	1.49	14.4	88.9	3.82	2.2
40	4.0	1.4	3.1	730	29.9	18.2	1.07	33.5	28.1	1.0	820	21.2	1.61	15.9	94.0	3.88	2.3
	4.0	1.4	3.1	850	30.6	20.0	1.11	34.4	27.5	1.0	950	21.6	1.54	16.4	91.1	4.12	2.3
	6.0	2.8	6.5	730	30.2	18.3	1.01	33.6	29.8	0.9	820	22.2	1.63	16.7	95.0	3.99	2.4
	6.0	2.8	6.5	850	30.9	20.0	1.06	34.5	29.2	0.9	950	22.6	1.56	17.3	92.0	4.24	2.4
	8.0	4.6	10.5	730	30.3	18.3	0.99	33.6	30.7	0.8	820	22.7	1.64	17.2	95.6	4.05	2.5
	8.0	4.6	10.5	850	31.0	20.0	1.03	34.5	30.1	0.9	950	23.1	1.57	17.8	92.5	4.31	2.5
50	4.0	1.3	2.9	730	29.1	18.3	1.17	33.1	24.8	1.6	820	24.4	1.69	18.7	97.5	4.24	2.6
	4.0	1.3	2.9	850	29.8	20.0	1.23	34.0	24.3	1.6	950	24.9	1.62	19.4	94.2	4.51	2.7
	6.0	2.6	6.1	730	29.6	18.4	1.11	33.4	26.7	1.4	820	25.4	1.71	19.6	98.7	4.34	2.7
	6.0	2.6	6.1	850	30.3	20.1	1.16	34.3	26.1	1.5	950	25.9	1.64	20.3	95.2	4.62	2.8
	8.0	4.3	9.9	730	29.9	18.4	1.08	33.5	27.6	1.3	820	25.9	1.73	20.1	99.3	4.40	2.8
	8.0	4.3	9.9	850	30.6	20.2	1.13	34.4	27.0	1.3	950	26.4	1.66	20.8	95.7	4.68	2.9
60	4.0	1.2	2.8	730	28.0	17.9	1.30	32.4	21.6	2.2	820	27.2	1.77	21.3	100.8	4.52	2.9
	4.0	1.2	2.8	850	28.6	19.6	1.35	33.3	21.2	2.2	950	27.8	1.69	22.0	97.1	4.81	3.0
	6.0	2.5	5.7	730	28.7	18.1	1.23	32.8	23.4	2.0	820	28.3	1.8	22.2	101.9	4.62	3.1
	6.0	2.5	5.7	850	29.3	19.9	1.28	33.7	22.9	2.0	950	28.8	1.72	23.0	98.1	4.91	3.1
	8.0	4.0	9.3	730	29.0	18.2	1.19	33.0	24.3	1.7	820	28.8	1.81	22.7	102.6	4.66	3.2
	8.0	4.0	9.3	850	29.7	20.0	1.24	33.9	23.8	1.8	950	29.4	1.74	23.5	98.6	4.96	3.2
70	4.0	1.1	2.6	730	26.6	17.3	1.43	31.4	18.5	2.9	820	29.9	1.84	23.6	103.7	4.75	3.3
	4.0	1.1	2.6	850	27.2	19.0	1.50	32.3	18.2	3.0	950	30.5	1.77	24.4	99.7	5.05	3.3
	6.0	2.3	5.4	730	27.4	17.7	1.36	31.9	20.2	2.6	820	31.0	1.88	24.6	105.0	4.83	3.4
	6.0	2.3	5.4	850	28.0	19.4	1.42	32.8	19.8	2.7	950	31.6	1.80	25.4	100.8	5.14	3.5
	8.0	3.8	8.7	730	27.7	17.8	1.32	32.2	21.0	2.3	820	31.5	1.90	25.1	105.6	4.87	3.5
	8.0	3.8	8.7	850	28.4	19.5	1.38	33.1	20.6	2.4	950	32.1	1.82	25.9	101.3	5.18	3.6
80	4.0	1.0	2.4	730	25.0	16.6	1.59	30.4	15.7	3.5	820	32.3	1.92	25.8	106.5	4.93	3.6
	4.0	1.0	2.4	850	25.6	18.3	1.66	31.2	15.4	3.6	950	33.0	1.84	26.7	102.1	5.24	3.6
	6.0	2.2	5.0	730	25.8	17.0	1.50	30.9	17.2	3.2	820	33.5	1.96	26.8	107.8	5.01	3.7
	6.0	2.2	5.0	850	26.4	18.7	1.57	31.8	16.8	3.3	950	34.1	1.88	27.7	103.2	5.32	3.8
	8.0	3.5	8.1	730	26.3	17.2	1.46	31.2	17.9	3.0	820	34.0	1.98	27.3	108.4	5.04	3.9
	8.0	3.5	8.1	850	26.9	18.9	1.53	32.1	17.6	3.0	950	34.7	1.90	28.2	103.8	5.36	3.9
85	4.0	1.0	2.4	730	24.2	16.3	1.68	29.9	14.4	3.9	820	33.5	1.96	26.8	107.9	5.01	3.7
	4.0	1.0	2.4	850	24.7	17.8	1.75	30.7	14.1	4.0	950	34.2	1.88	27.8	103.3	5.33	3.8
	6.0	2.1	4.9	730	25.0	16.7	1.59	30.4	15.7	3.6	820	34.7	2.00	27.8	109.1	5.08	3.9
	6.0	2.1	4.9	850	25.6	18.3	1.66	31.3	15.4	3.7	950	35.3	1.92	28.8	104.4	5.40	3.9
	8.0	3.4	7.9	730	25.4	16.8	1.55	30.7	16.5	3.3	820	35.2	2.02	28.4	109.8	5.12	4.0
	8.0	3.4	7.9	850	26.0	18.5	1.61	31.5	16.1	3.4	950	35.9	1.93	29.3	105.0	5.44	4.1
90	4.0	1.0	2.3	730	23.3	15.9	1.77	29.4	13.2	4.6	820	34.7	2.00	27.9	109.2	5.09	3.9
	4.0	1.0	2.3	850	23.9	17.4	1.84	30.2	13.0	4.6	950	35.4	1.92	28.8	104.5	5.41	3.9
	6.0	2.1	4.8	730	24.2	16.3	1.67	29.9	14.4	4.1	820	35.9	2.04	28.9	110.5	5.16	4.0
	6.0	2.1	4.8	850	24.7	17.9	1.75	30.7	14.2	4.2	950	36.6	1.95	29.9	105.6	5.48	4.1
	8.0	3.4	7.8	730	24.6	16.5	1.63	30.2	15.1	3.8	820	36.5	2.06	29.4	111.2	5.19	4.2
	8.0	3.4	7.8	850	25.2	18.1	1.70	31.0	14.8	3.9	950	37.2	1.97	30.4	106.2	5.52	4.3
100	4.0	1.0	2.2	730	21.7	15.2	1.97	28.4	11.0	4.9	Operation not recommended						
	4.0	1.0	2.2	850	22.2	16.7	2.05	29.2	10.8	5.0							
	6.0	2.0	4.6	730	22.5	15.5	1.86	28.9	12.1	4.7							
	6.0	2.0	4.6	850	23.0	17.0	1.95	29.7	11.8	4.8							
	8.0	3.2	7.4	730	22.9	15.7	1.81	29.1	12.6	4.5							
	8.0	3.2	7.4	850	23.4	17.2	1.89	29.9	12.4	4.6							
110	4.0	0.9	2.1	730	20.1	14.6	2.19	27.7	9.2	5.8	Operation not recommended						
	4.0	0.9	2.1	850	20.6	16.0	2.29	28.4	9.0	6.0							
	6.0	1.9	4.4	730	20.9	14.8	2.08	28.0	10.0	5.6							
	6.0	1.9	4.4	850	21.3	16.3	2.17	28.8	9.8	5.8							
	8.0	3.1	7.2	730	21.2	15.0	2.03	28.2	10.5	5.4							
	8.0	3.1	7.2	850	21.7	16.4	2.11	29.0	10.3	5.5							
120	4.0	0.9	2.0	730	18.8	14.1	2.45	27.2	7.7	6.9	Operation not recommended						
	4.0	0.9	2.0	850	19.2	15.5	2.55	28.0	7.5	7.1							
	6.0	1.8	4.2	730	19.4	14.3	2.32	27.4	8.3	6.7							
	6.0	1.8	4.2	850	19.8	15.7	2.43	28.2	8.2	6.8							
	8.0	3.0	6.9	730	19.7	14.4	2.26	27.5	8.7	6.4							
	8.0	3.0	6.9	850	20.2	15.8	2.36	28.3	8.5	6.5							

ClimateMaster Tranquility® 27 Model 026 — Part Load Mode Performance Data

(http://www.climatemaster.com/share/Res_All_Products_CLM/Section_3_TT27.pdf)

725 CFM Nominal (ISO Rated) Airflow Cooling, 825 CFM Nominal (ISO Rated) Airflow Heating

Performance capacities shown in thousands of Btu/h

EWT °F	GPM	WPD		Cooling - EAT 80/67°F							Heating - EAT 70°F						
		PSI	FT	Airflow CFM	TC	SC	kW	HR	EER	HW	Airflow CFM	HC	kW	HE	LAT	COP	HW
20	7.0	4.5	10.3	Operation not recommended							710	11.6	1.05	8.2	85.1	3.25	1.4
	7.0	4.5	10.3								825	11.7	1.02	8.4	83.2	3.38	1.5
30	3.5	1.2	2.8	620	22.2	14.0	0.58	24.1	38.3	0.5	710	13.6	1.09	10.1	87.8	3.66	1.6
	3.5	1.2	2.8	725	22.5	14.7	0.59	24.4	38.3	0.5	825	13.8	1.06	10.3	85.5	3.81	1.6
	5.8	2.9	6.6	620	22.4	14.0	0.57	24.3	39.2	0.4	710	14.2	1.09	10.7	88.5	3.81	1.6
	5.8	2.9	6.6	725	22.7	14.7	0.58	24.7	39.2	0.5	825	14.4	1.06	10.9	86.1	3.97	1.7
	7.0	4.1	9.4	620	22.5	14.0	0.56	24.4	39.8	0.4	710	14.4	1.09	10.9	88.8	3.86	1.7
	7.0	4.1	9.4	725	22.8	14.7	0.57	24.7	39.8	0.4	825	14.6	1.06	11.1	86.3	4.02	1.7
40	3.5	1.1	2.5	620	22.9	15.1	0.65	25.1	35.3	0.7	710	16.1	1.15	12.3	90.9	4.08	1.7
	3.5	1.1	2.5	725	23.3	15.8	0.66	25.5	35.3	0.7	825	16.2	1.12	12.6	88.2	4.25	1.7
	5.8	2.6	5.9	620	23.1	15.1	0.61	25.2	37.9	0.7	710	16.7	1.15	13.0	91.8	4.25	1.8
	5.8	2.6	5.9	725	23.4	15.9	0.62	25.5	37.9	0.7	825	16.9	1.12	13.3	89.0	4.42	1.8
	7.0	3.6	8.4	620	23.2	15.1	0.60	25.2	38.3	0.6	710	16.9	1.16	13.2	92.1	4.30	1.8
	7.0	3.6	8.4	725	23.5	15.9	0.61	25.6	38.3	0.6	825	17.1	1.12	13.5	89.2	4.47	1.8
50	3.5	1.0	2.3	620	22.7	15.4	0.74	25.2	30.7	1.1	710	18.3	1.18	14.5	93.9	4.56	1.8
	3.5	1.0	2.3	725	23.0	16.2	0.75	25.6	30.7	1.1	825	18.5	1.14	14.8	90.8	4.75	1.8
	5.8	2.4	5.6	620	22.9	15.5	0.69	25.3	33.4	1.0	710	19.1	1.18	15.2	94.8	4.73	1.9
	5.8	2.4	5.6	725	23.3	16.3	0.70	25.6	33.4	1.0	825	19.3	1.15	15.5	91.6	4.93	1.9
	7.0	3.4	7.9	620	23.0	15.5	0.67	25.3	34.1	0.9	710	19.3	1.18	15.4	95.1	4.78	1.9
	7.0	3.4	7.9	725	23.3	16.3	0.68	25.6	34.1	0.9	825	19.5	1.15	15.7	91.9	4.98	2.0
60	3.5	1.0	2.2	620	21.9	15.3	0.85	24.8	25.9	2.2	710	20.4	1.21	16.5	96.6	4.93	2.0
	3.5	1.0	2.2	725	22.2	16.1	0.86	25.1	25.9	2.2	825	20.6	1.18	16.8	93.2	5.13	2.0
	5.8	2.3	5.2	620	22.4	15.5	0.78	25.1	28.6	2.0	710	21.2	1.22	17.3	97.7	5.10	2.1
	5.8	2.3	5.2	725	22.7	16.3	0.80	25.4	28.6	2.0	825	21.5	1.18	17.6	94.1	5.31	2.1
	7.0	3.2	7.4	620	22.5	15.5	0.77	25.1	29.4	1.7	710	21.5	1.22	17.5	98.0	5.15	2.1
	7.0	3.2	7.4	725	22.9	16.3	0.78	25.5	29.4	1.8	825	21.7	1.19	17.8	94.3	5.36	2.2
70	3.5	0.9	2.1	620	20.7	14.8	0.97	24.0	21.4	1.9	710	22.4	1.23	18.4	99.2	5.35	2.2
	3.5	0.9	2.1	725	21.0	15.6	0.98	24.3	21.4	2.0	825	22.7	1.19	18.8	95.4	5.57	2.2
	5.8	2.1	4.9	620	21.4	15.1	0.90	24.4	23.8	1.8	710	23.3	1.24	19.3	100.4	5.52	2.2
	5.8	2.1	4.9	725	21.7	15.9	0.91	24.8	23.8	1.8	825	23.5	1.20	19.6	96.4	5.75	2.3
	7.0	3.0	7.0	620	21.6	15.2	0.88	24.6	24.5	1.6	710	23.5	1.24	19.5	100.7	5.57	2.3
	7.0	3.0	7.0	725	21.9	16.0	0.89	24.9	24.5	1.6	825	23.8	1.20	19.9	96.7	5.80	2.4
80	3.5	0.8	1.9	620	19.3	14.2	1.10	23.1	17.5	2.5	710	24.4	1.25	20.3	101.8	5.73	2.3
	3.5	0.8	1.9	725	19.6	14.9	1.12	23.4	17.5	2.5	825	24.6	1.21	20.7	97.7	5.97	2.3
	5.8	2.0	4.6	620	20.1	14.5	1.03	23.6	19.5	2.3	710	25.3	1.26	21.2	103.0	5.90	2.4
	5.8	2.0	4.6	725	20.4	15.3	1.04	23.9	19.5	2.3	825	25.6	1.22	21.6	98.7	6.15	2.4
	7.0	2.8	6.5	620	20.3	14.6	1.01	23.7	20.1	2.1	710	25.6	1.26	21.5	103.4	5.95	2.5
	7.0	2.8	6.5	725	20.6	15.4	1.02	24.0	20.1	2.2	825	25.9	1.22	21.9	99.0	6.20	2.5
85	3.5	0.8	1.9	620	18.7	13.9	1.18	22.7	15.9	2.9	710	25.3	1.26	21.2	103.0	5.91	2.4
	3.5	0.8	1.9	725	18.9	14.6	1.19	23.0	15.9	3.0	825	25.6	1.22	21.7	98.7	6.15	2.4
	5.8	1.9	4.5	620	19.3	14.2	1.10	23.1	17.5	2.7	710	26.3	1.27	22.2	104.3	6.08	2.5
	5.8	1.9	4.5	725	19.6	14.9	1.12	23.4	17.5	2.8	825	26.6	1.23	22.6	99.9	6.33	2.5
	7.0	2.7	6.3	620	19.5	14.3	1.08	23.2	18.0	2.5	710	26.6	1.27	22.5	104.7	6.13	2.6
	7.0	2.7	6.3	725	19.8	15.0	1.10	23.6	18.0	2.6	825	26.9	1.24	22.9	100.2	6.38	2.6
90	3.5	0.8	1.8	620	18.0	13.7	1.25	22.3	14.4	3.3	710	26.3	1.27	22.2	104.3	6.08	2.5
	3.5	0.8	1.8	725	18.3	14.4	1.27	22.6	14.4	3.4	825	26.6	1.23	22.6	99.8	6.33	2.5
	5.8	1.9	4.4	620	18.6	13.8	1.18	22.6	15.8	3.1	710	27.3	1.28	23.1	105.6	6.25	2.5
	5.8	1.9	4.4	725	18.9	14.6	1.20	22.9	15.8	3.1	825	27.6	1.24	23.6	101.0	6.51	2.6
	7.0	2.7	6.2	620	18.8	13.9	1.16	22.7	16.3	2.8	710	27.6	1.28	23.4	106.0	6.30	2.6
	7.0	2.7	6.2	725	19.1	14.7	1.17	23.1	16.3	2.9	825	27.9	1.25	23.9	101.3	6.56	2.7
100	3.5	0.8	1.8	620	16.6	13.0	1.41	21.4	11.7	3.9	Operation not recommended						
	3.5	0.8	1.8	725	16.8	13.7	1.43	21.7	11.7	4.0							
	5.8	1.8	4.2	620	17.1	13.2	1.34	21.7	12.7	3.7							
	5.8	1.8	4.2	725	17.4	13.8	1.36	22.0	12.7	3.8							
	7.0	2.6	6.0	620	17.3	13.3	1.32	21.8	13.1	3.6							
	7.0	2.6	6.0	725	17.5	13.9	1.34	22.1	13.1	3.7							
110	3.5	0.7	1.7	620	15.5	12.7	1.59	20.9	9.7	5.0	Operation not recommended						
	3.5	0.7	1.7	725	15.7	13.4	1.61	21.2	9.7	5.1							
	5.8	1.7	4.0	620	15.8	12.7	1.53	21.0	10.3	4.8							
	5.8	1.7	4.0	725	16.0	13.3	1.55	21.3	10.3	4.9							
	7.0	2.5	5.7	620	16.0	12.7	1.50	21.1	10.6	4.6							
	7.0	2.5	5.7	725	16.2	13.4	1.52	21.4	10.6	4.7							
120	3.5	0.7	1.6	620	14.5	12.6	1.84	20.8	7.9	6.3	Operation not recommended						
	3.5	0.7	1.6	725	14.7	13.3	1.86	21.1	7.9	6.4							
	5.8	1.7	3.9	620	14.8	12.5	1.73	20.7	8.6	6.0							
	5.8	1.7	3.9	725	15.0	13.2	1.76	21.0	8.6	6.2							
	7.0	2.4	5.5	620	14.9	12.5	1.71	20.7	8.7	5.8							
	7.0	2.4	5.5	725	15.1	13.2	1.73	21.0	8.7	5.9							

APPENDIX B. MEASURED PERFORMANCE DATA

APPENDIX B: MEASURED PERFORMANCE DATA

B-1: DECEMBER 2011

Unit 01 (925)

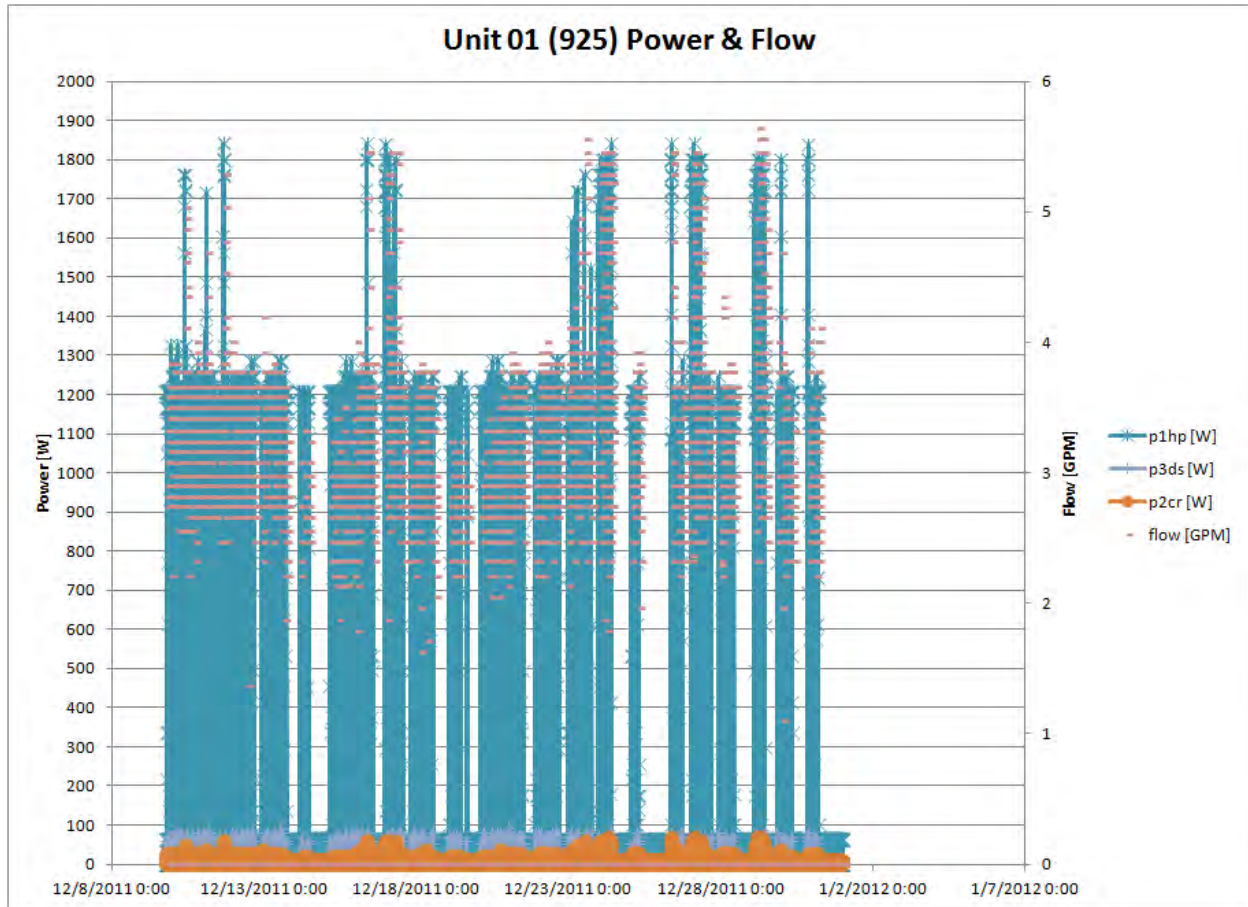


Figure B-1-1-1. Measured power and flow rate

Explanation of the legend in the above chart:

- P1hp: Power draw of the total GSHP system
- P3ds: Power draw of the circulator in the desuperheater
- P2cr: Power draw of the circulation pump of GSHP system
- Flow: Fluid flow rate in the GHX

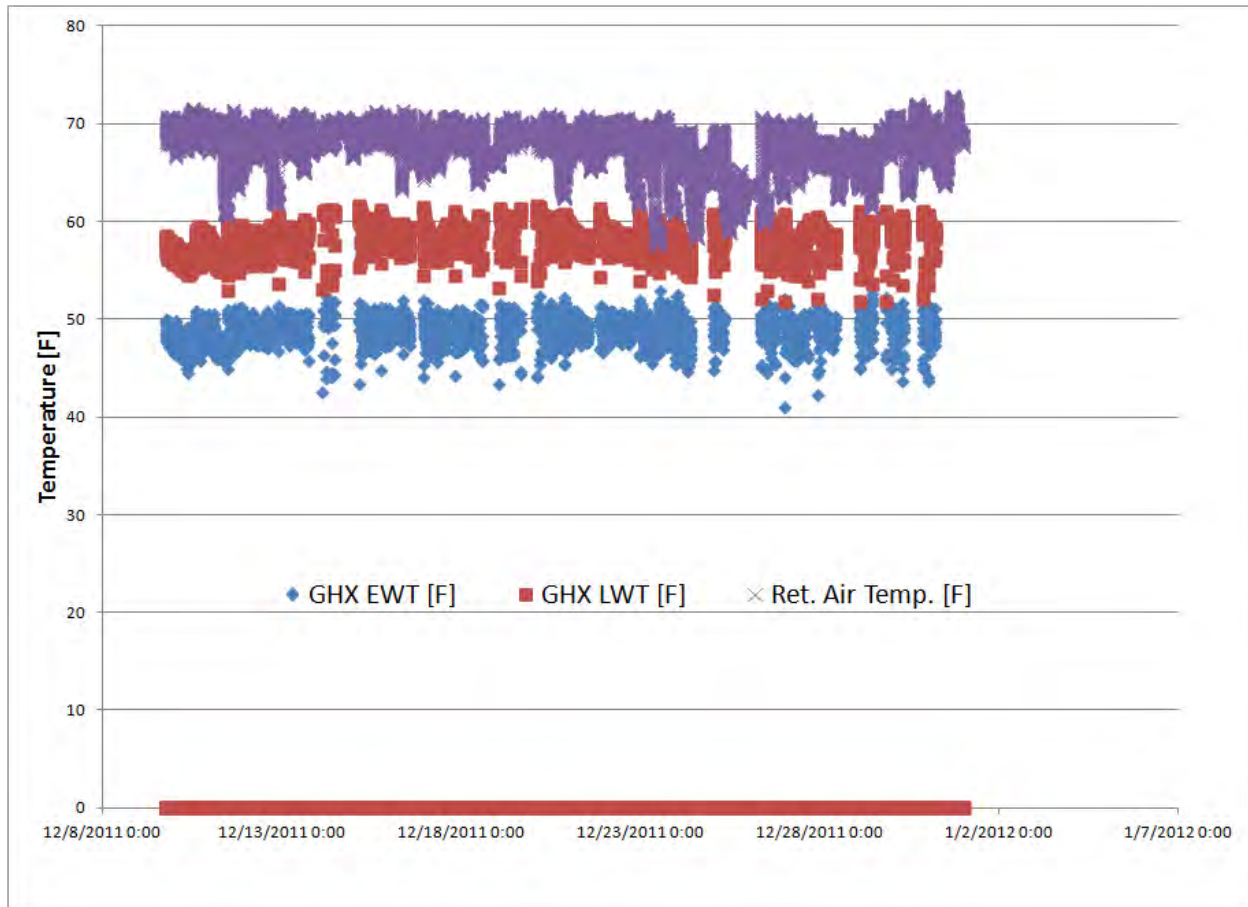


Figure B-1-1-2. Measured room and loop temperatures

Explanation of the legend in the above chart:

GHX EWT: Entering fluid temperature of the GHX

GHX LWT: Leaving fluid temperature of the GHX

Ret. Air Temp: Room temperature

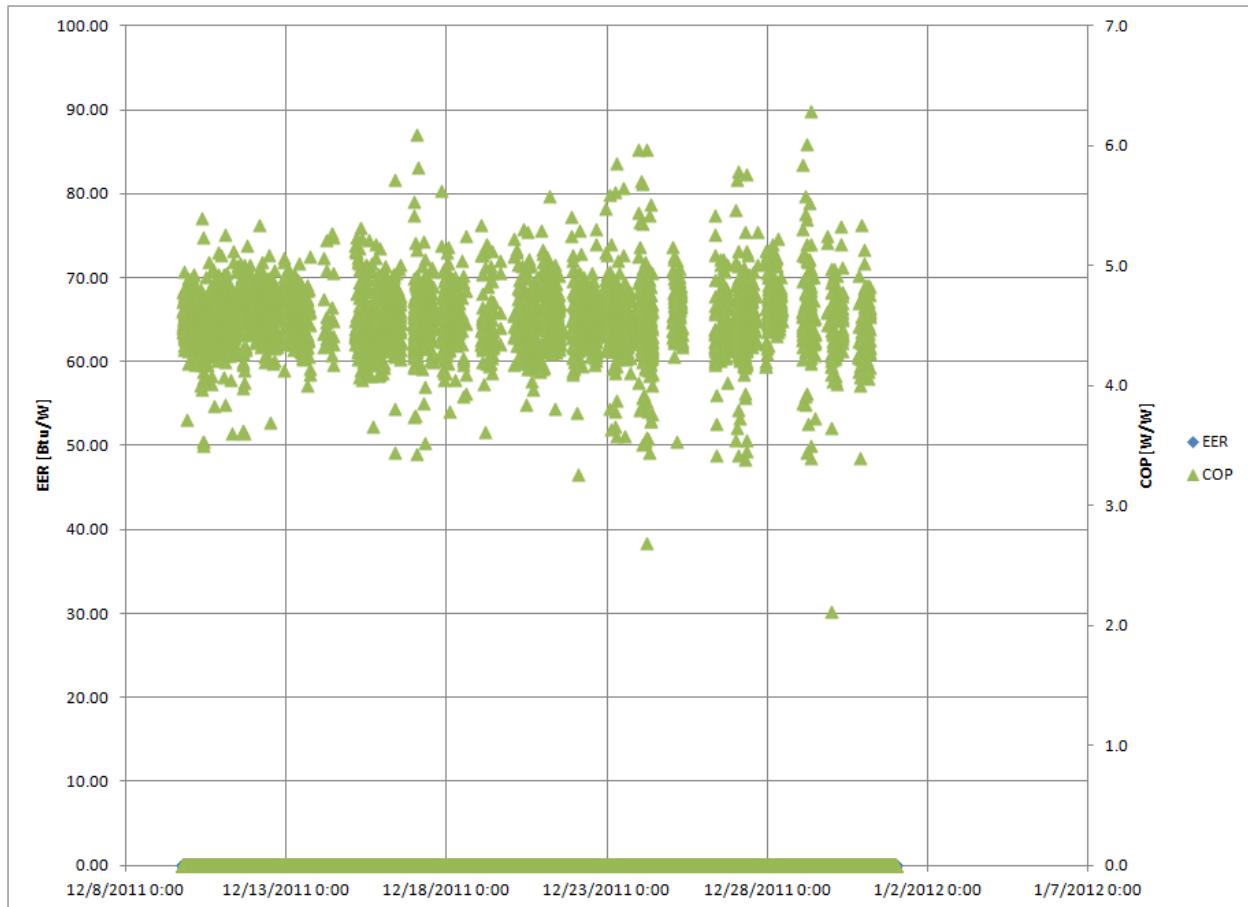


Figure B-1-1-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Explanation of the legend in the above chart:

- COP: System COP (does not separate the effect of the desuper-heater)
- EER: System EER (does not separate the effect of the desuper-heater)

Unit 02 (916)

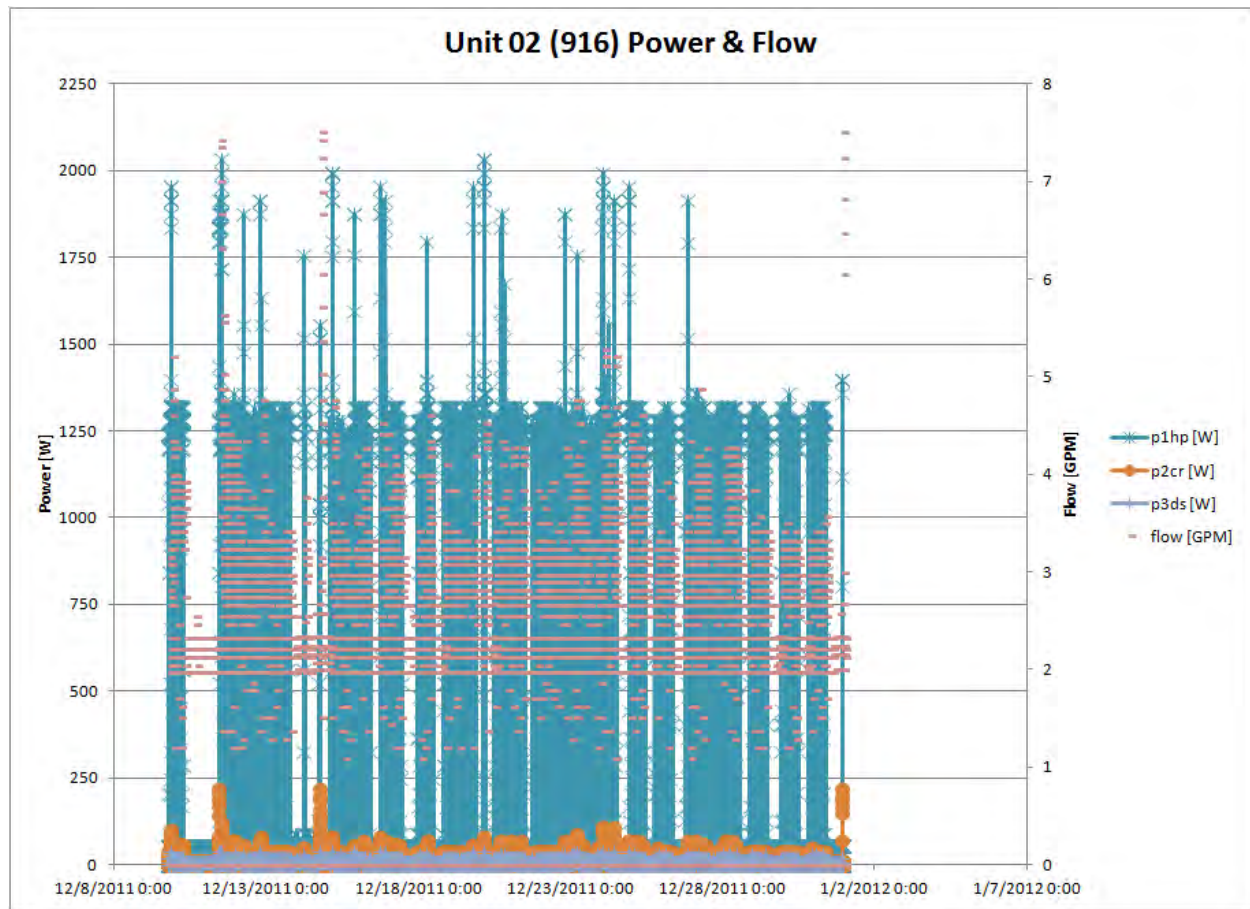


Figure B-1-2-1. Measured power and flow rate

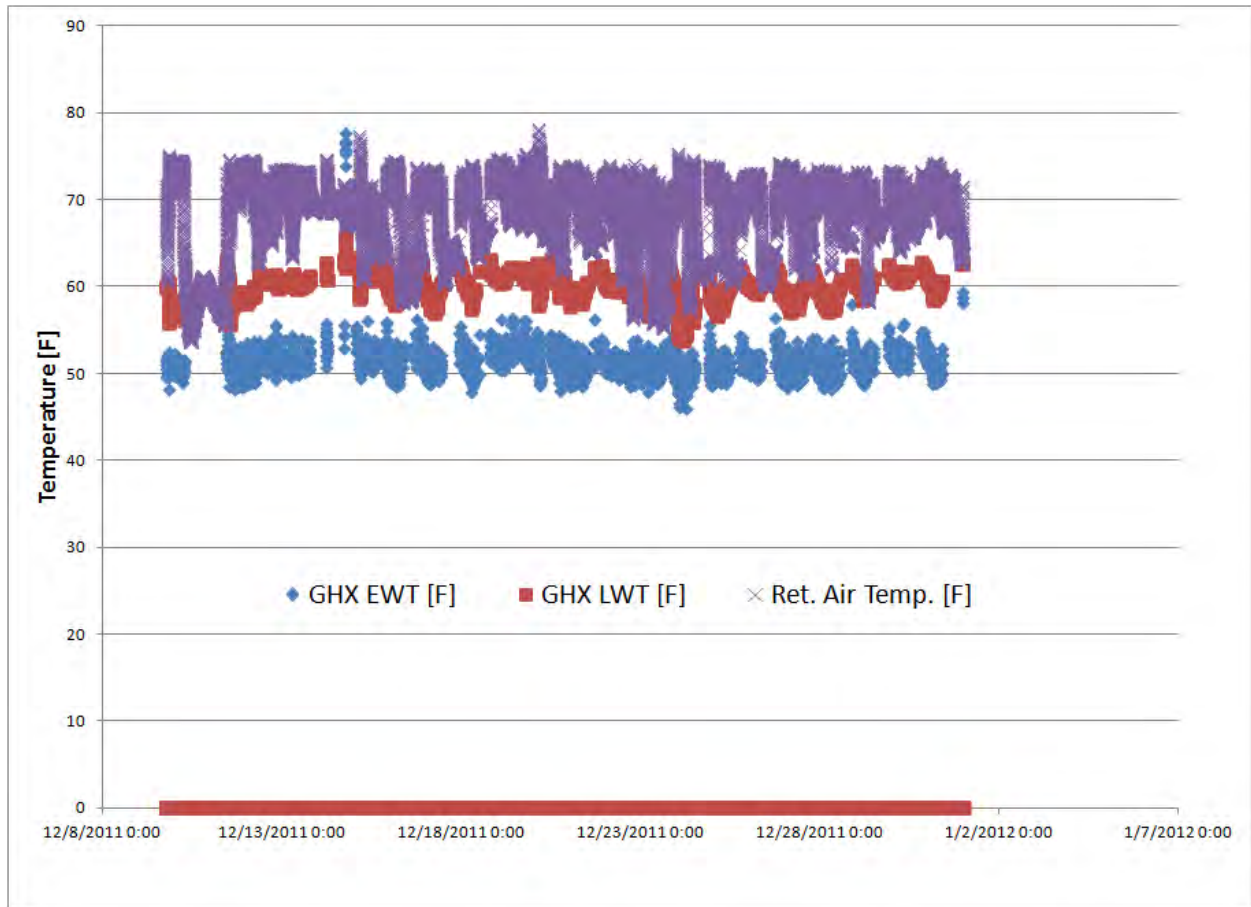


Figure B-1-2-2. Measured room and loop temperatures

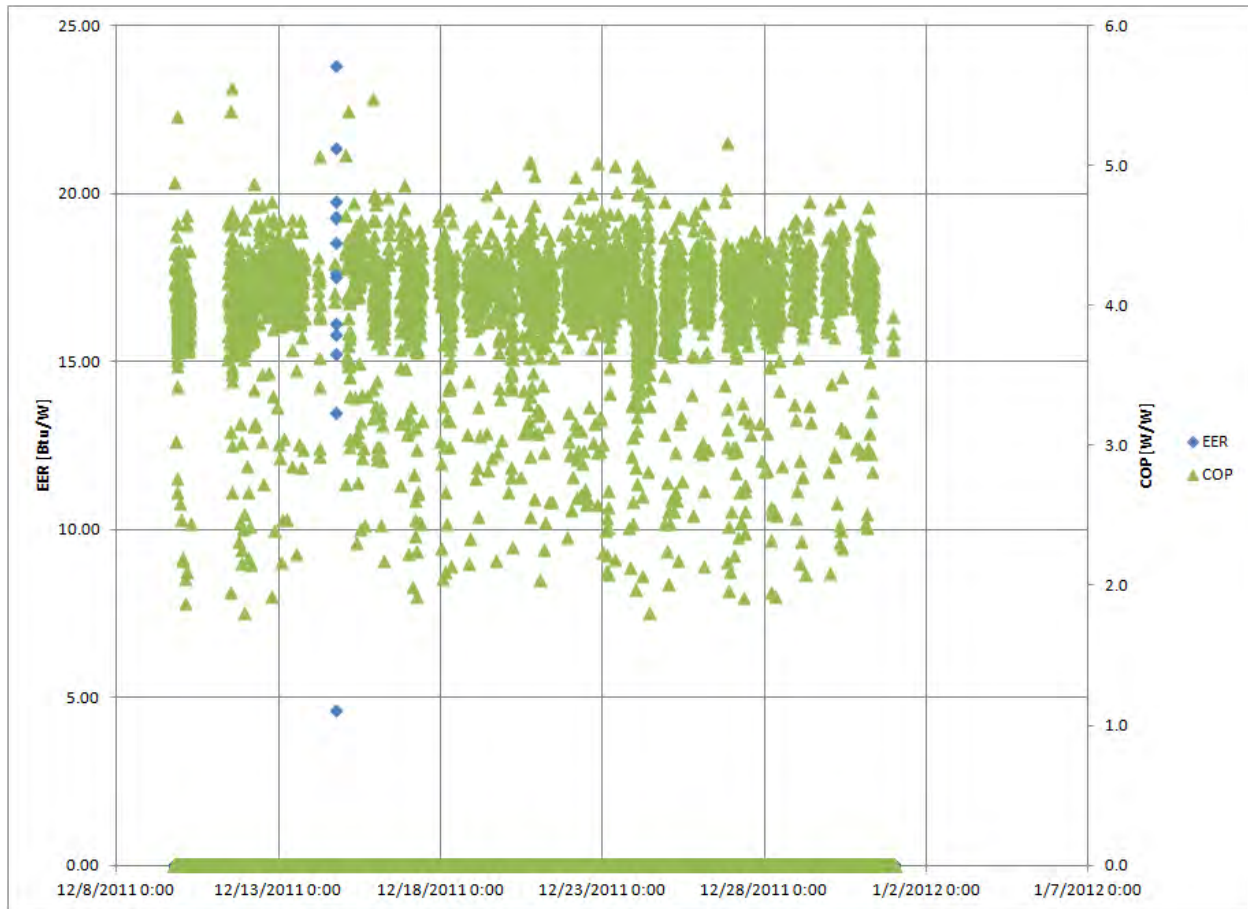


Figure B-1-2-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 03 (833)

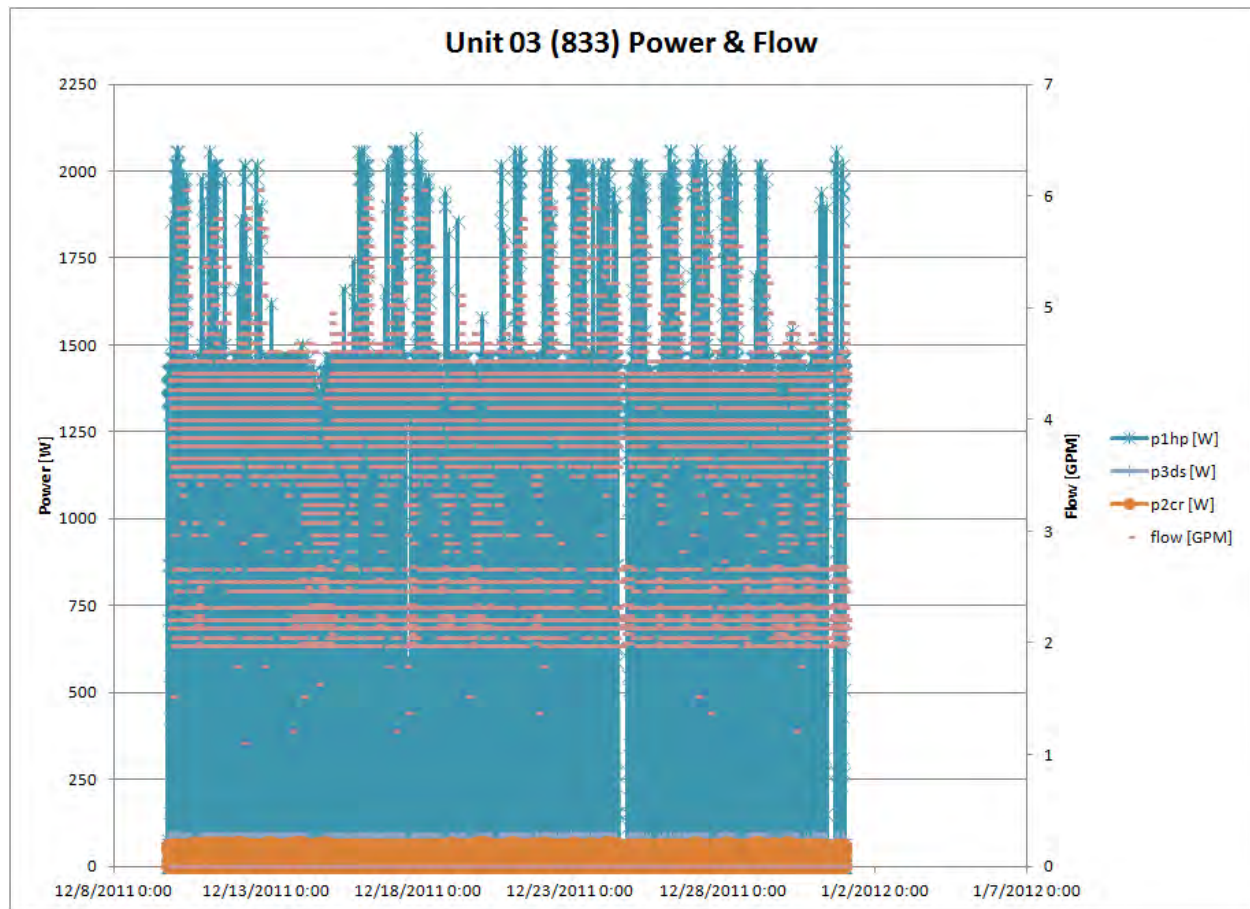


Figure B-1-3-1. Measured power and flow rate

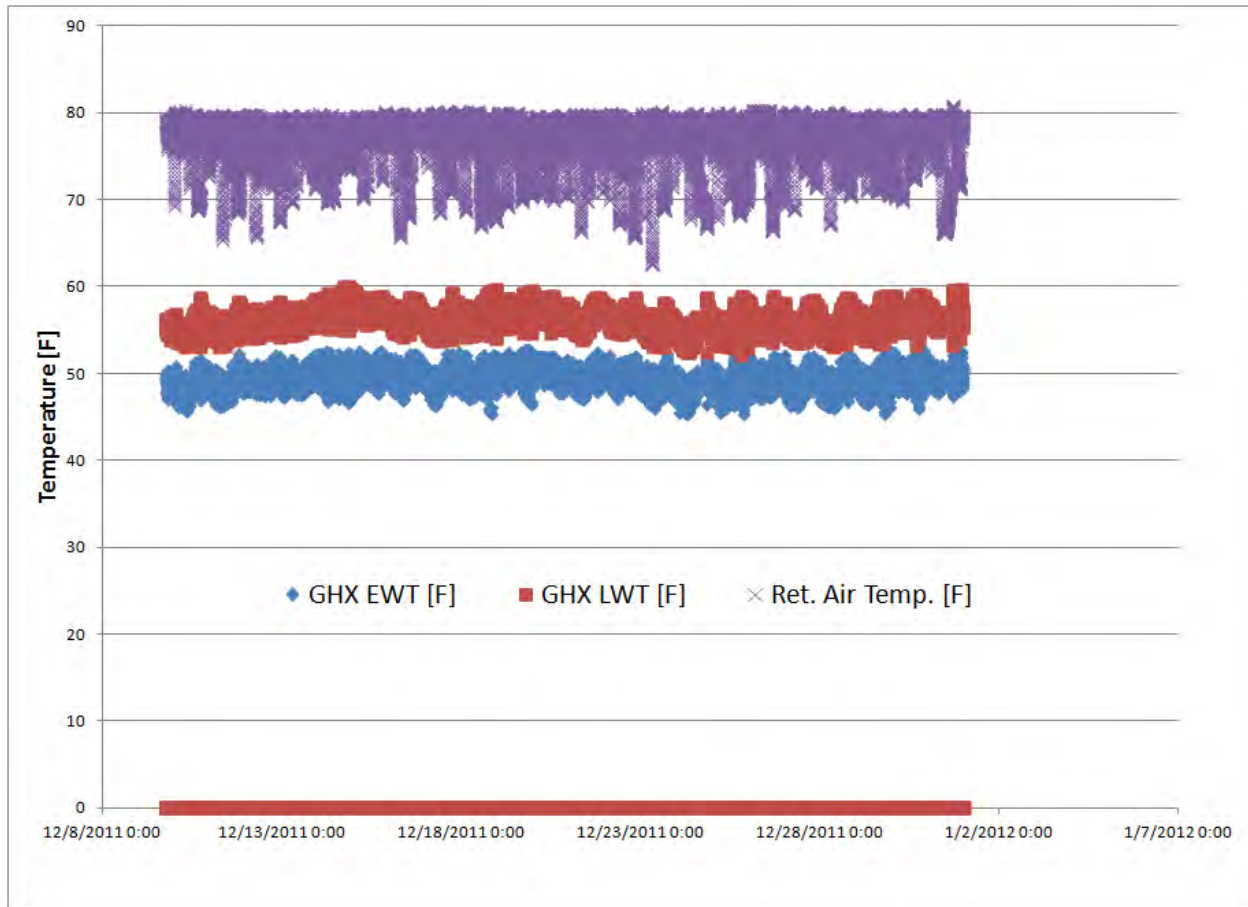


Figure B-1-3-2. Measured room and loop temperatures

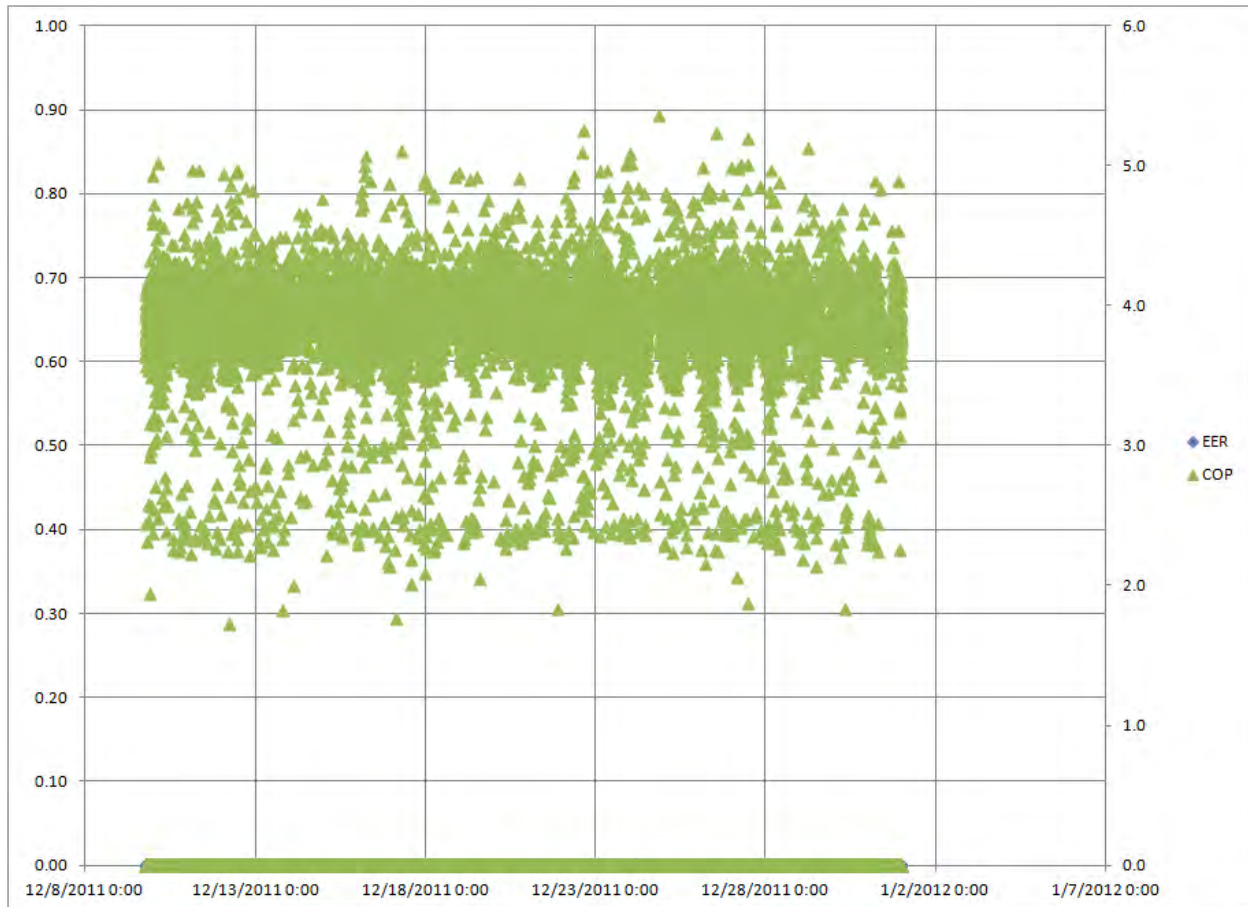


Figure B-1-3-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 04 (932)

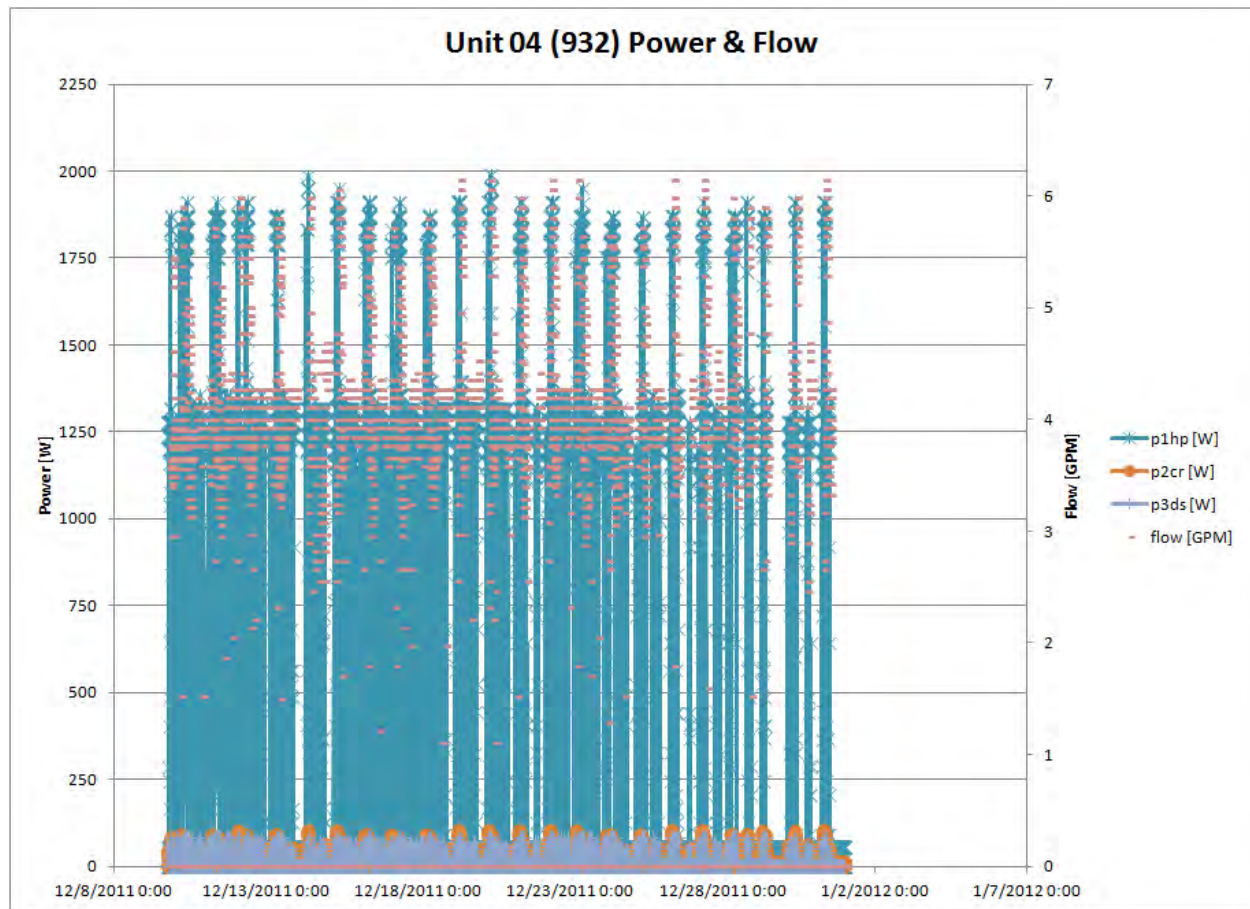


Figure B-1-4-1. Measured power and flow rate

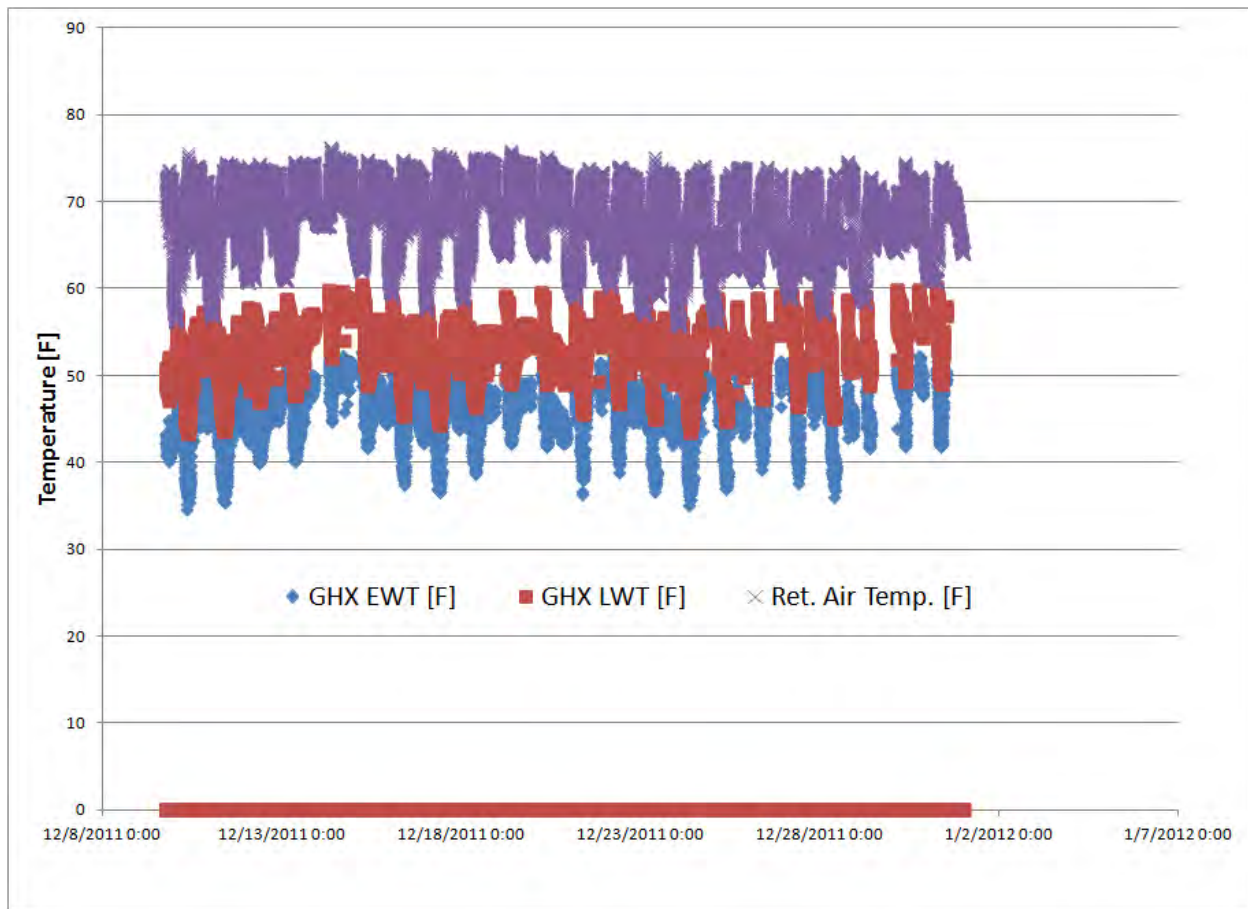


Figure B-1-4-2. Measured room and loop temperatures

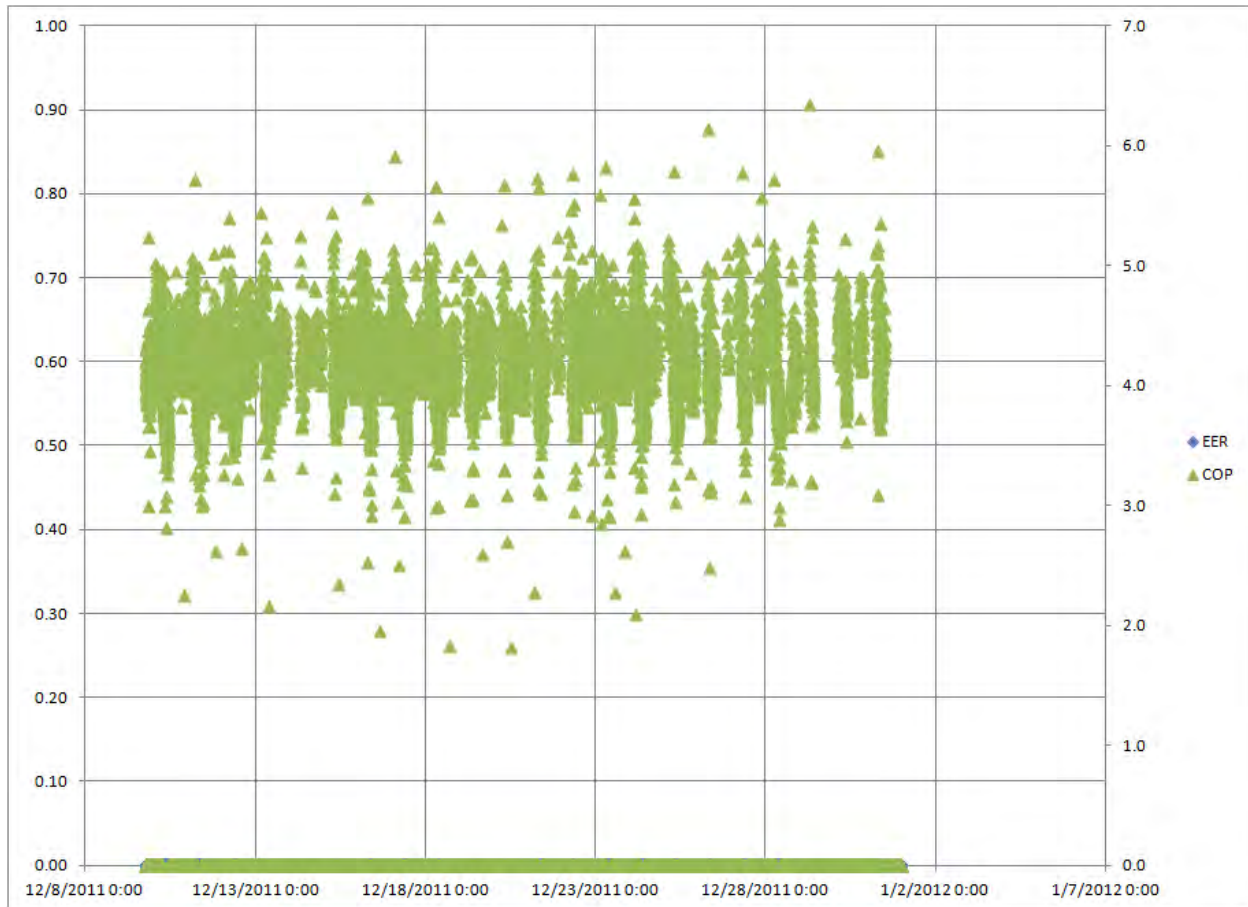


Figure B-1-4-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 05 (813)

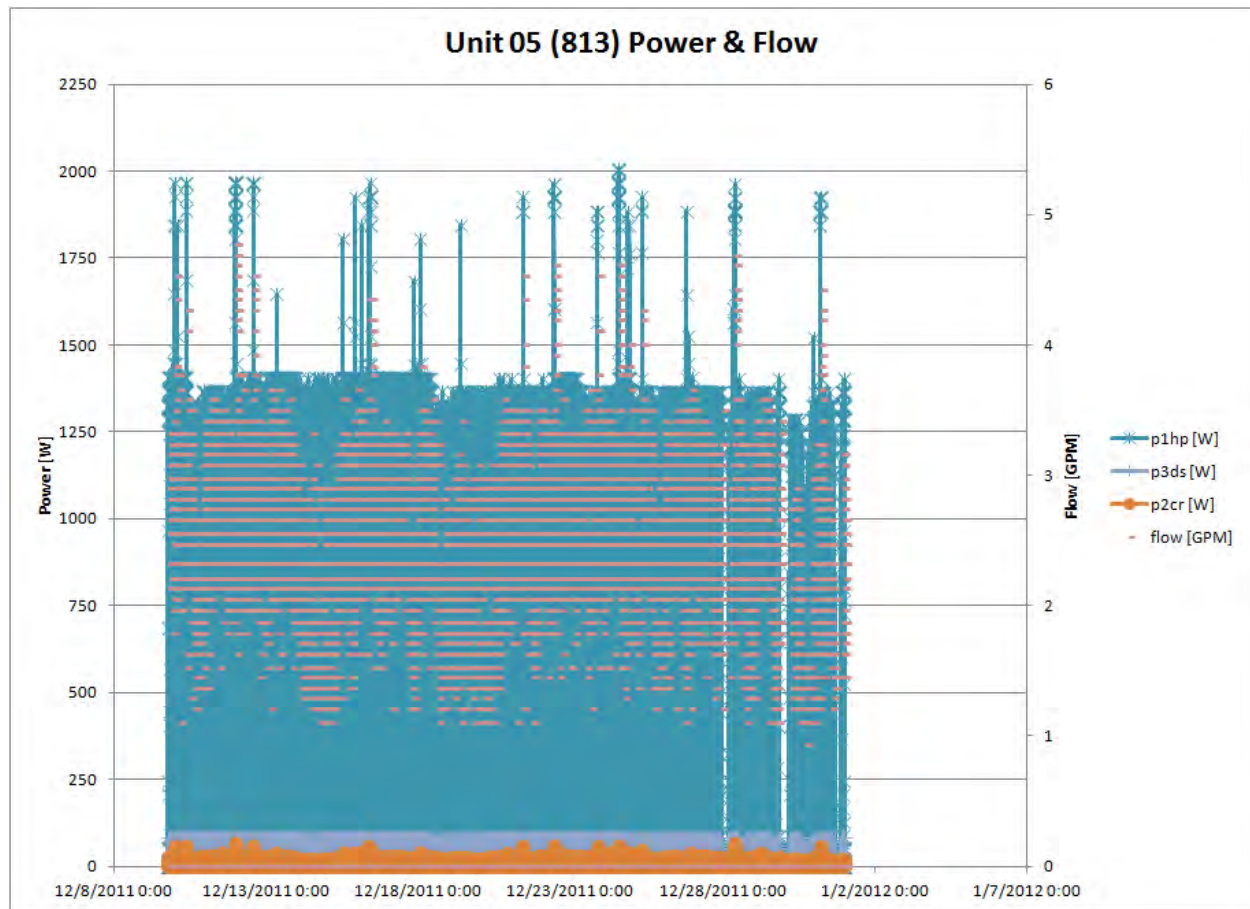


Figure B-1-5-1. Measured power and flow rate

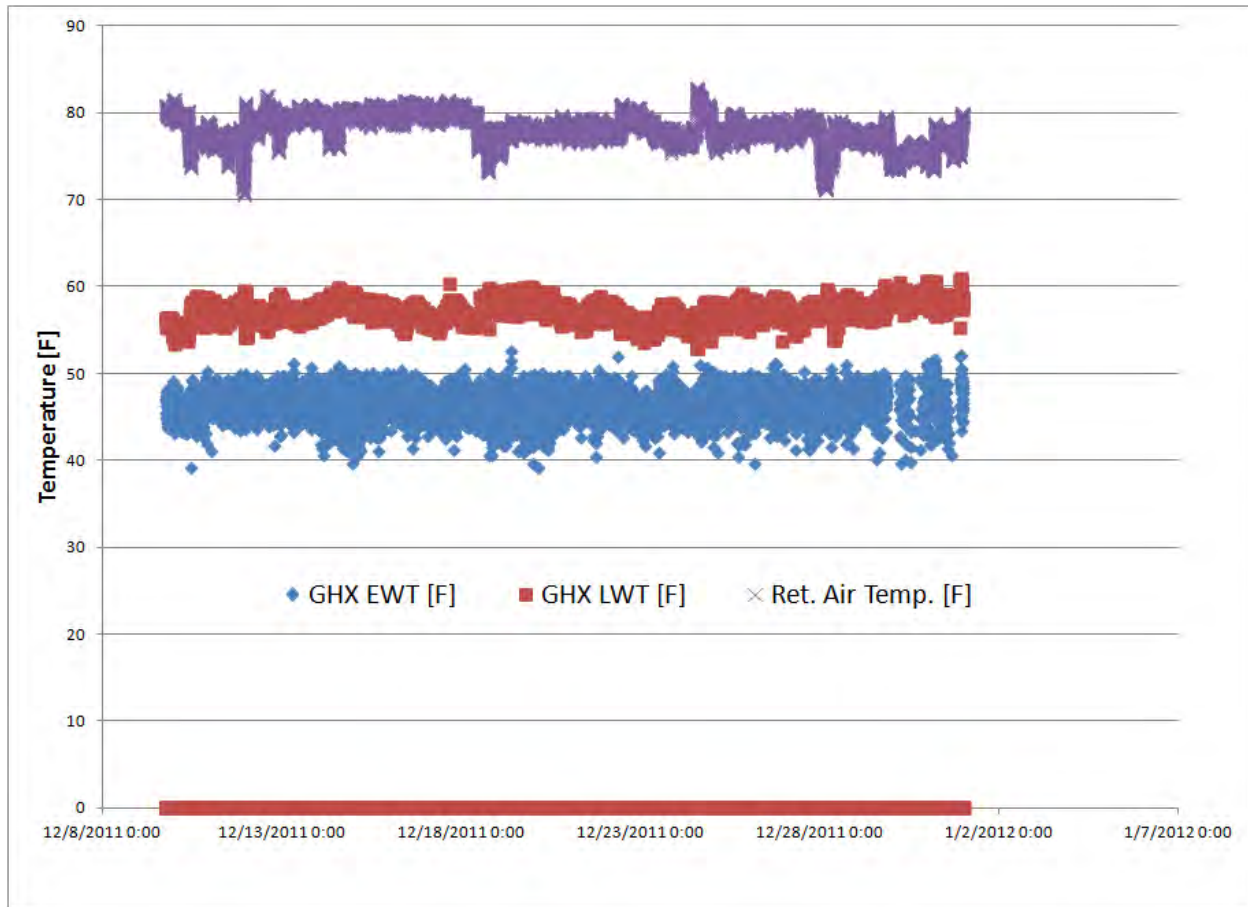


Figure B-1-5-2. Measured room and loop temperatures

The house has the highest room temperature set-point (around 80°F) and the thermostat in this home has a very narrow dead band for temperature control. As a result, the heat pump runs almost continuously all the time and mostly in part-load mode. It may explain the relatively lower COP at this home since the ground has little time to recover from the heat extraction.

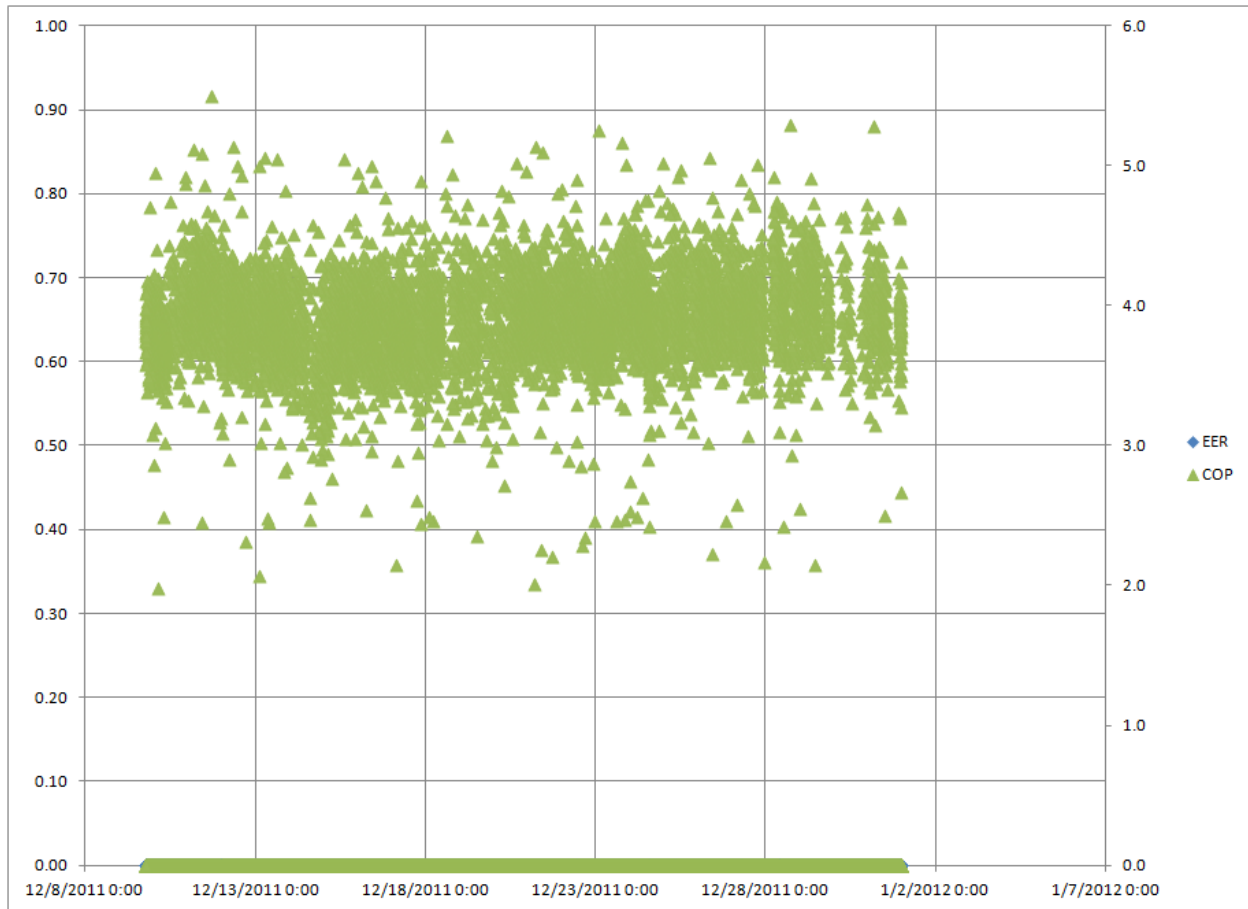


Figure B-1-5-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 06 (824)

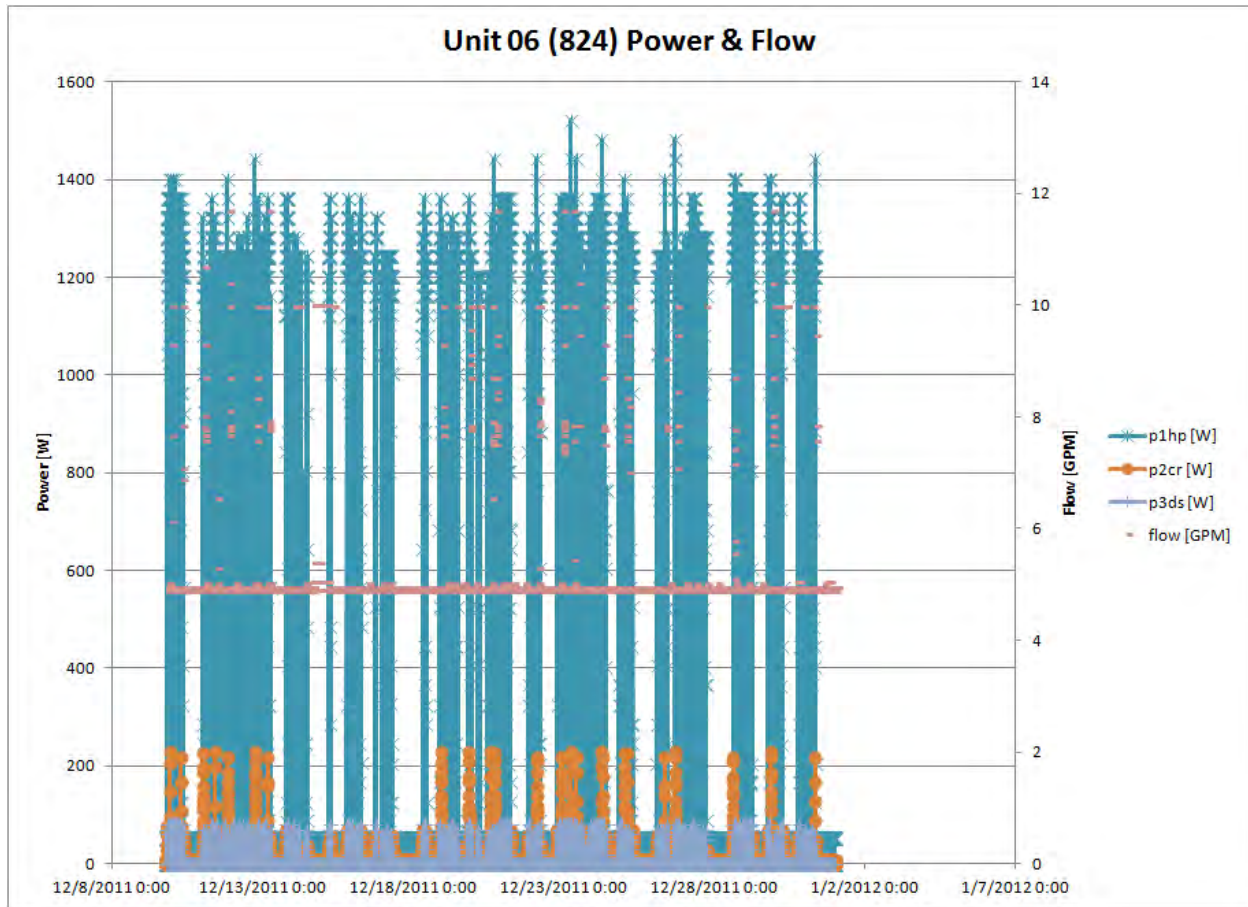


Figure B-1-6-1. Measured power and flow rate

The flow rate shown in the chart is from invalid flow rate measurement.

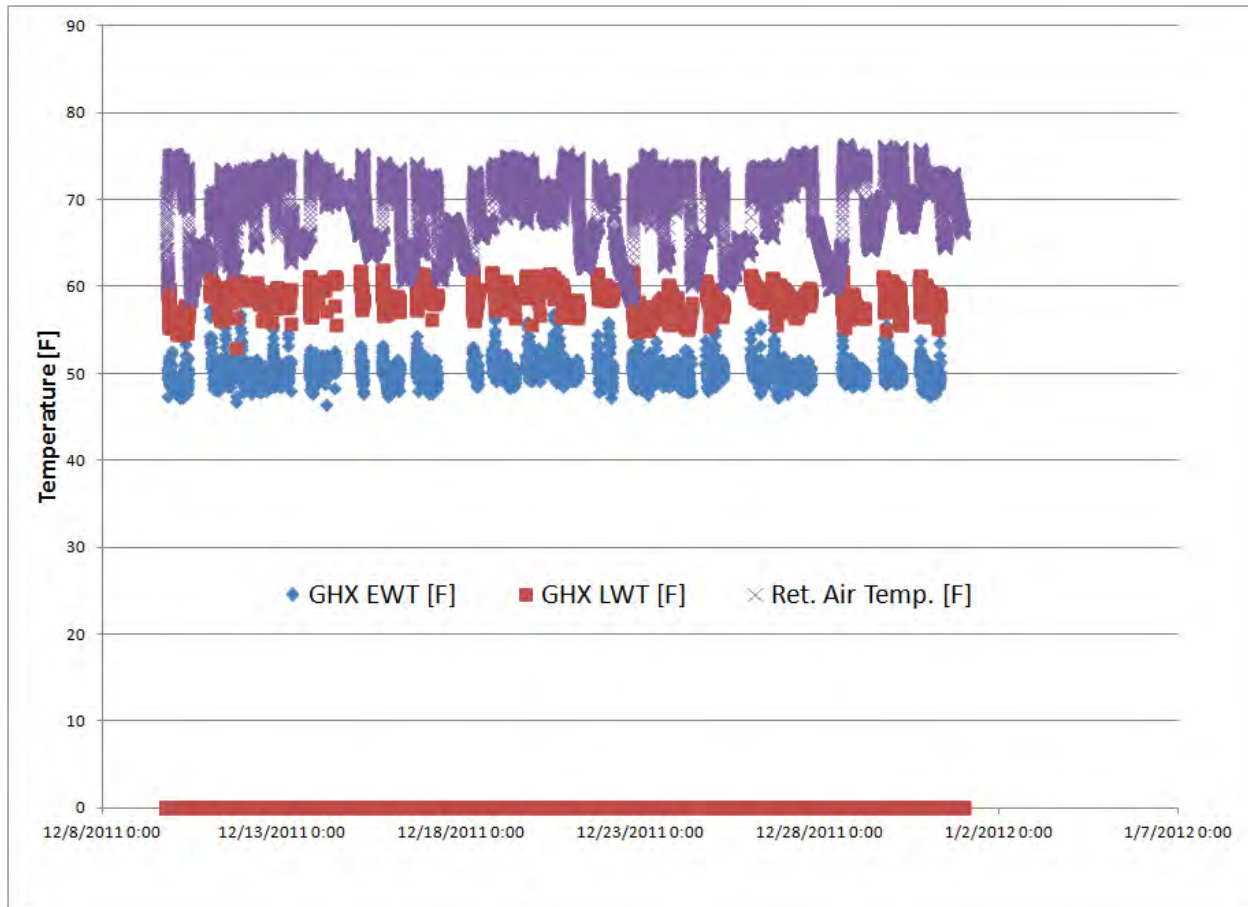


Figure 15-2. Measured room and loop temperatures

The house has a modest room temperature set-point (around 75°F).

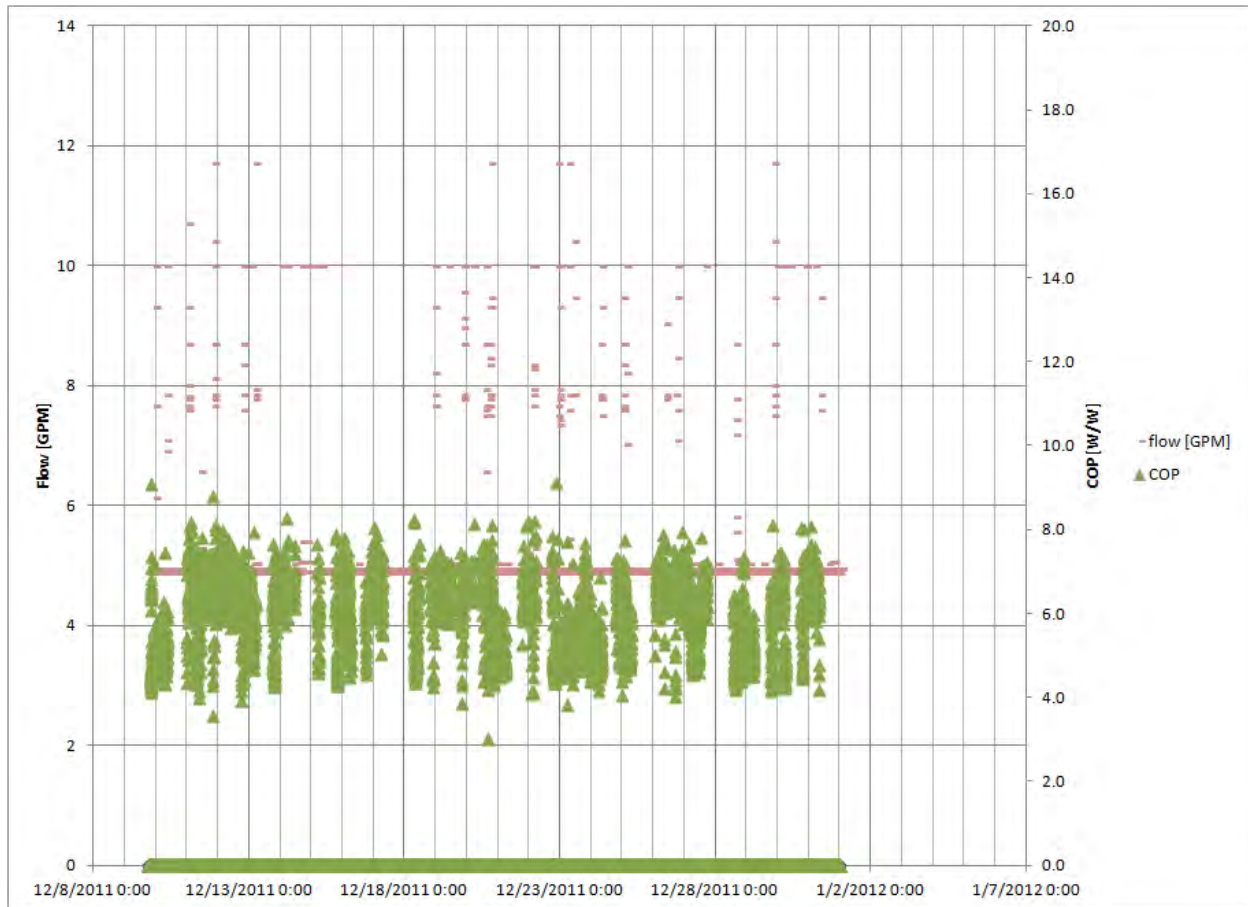


Figure B-1-6-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

The high COP is invalid due to the inaccurate flow rate measurements.

Unit 07 (928)

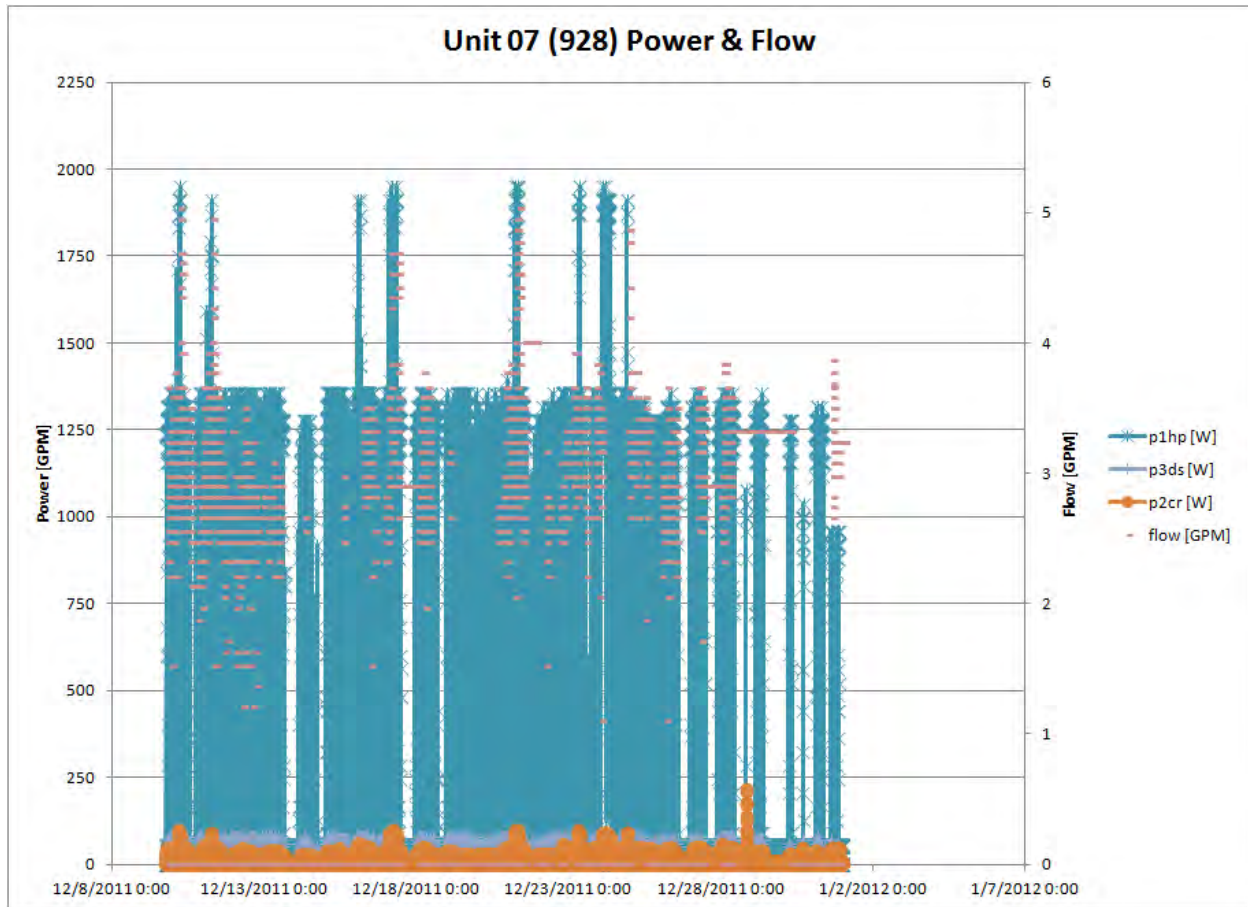


Figure B-1-7-1. Measured power and flow rate

The above chart indicates that some flow data was missing in December.

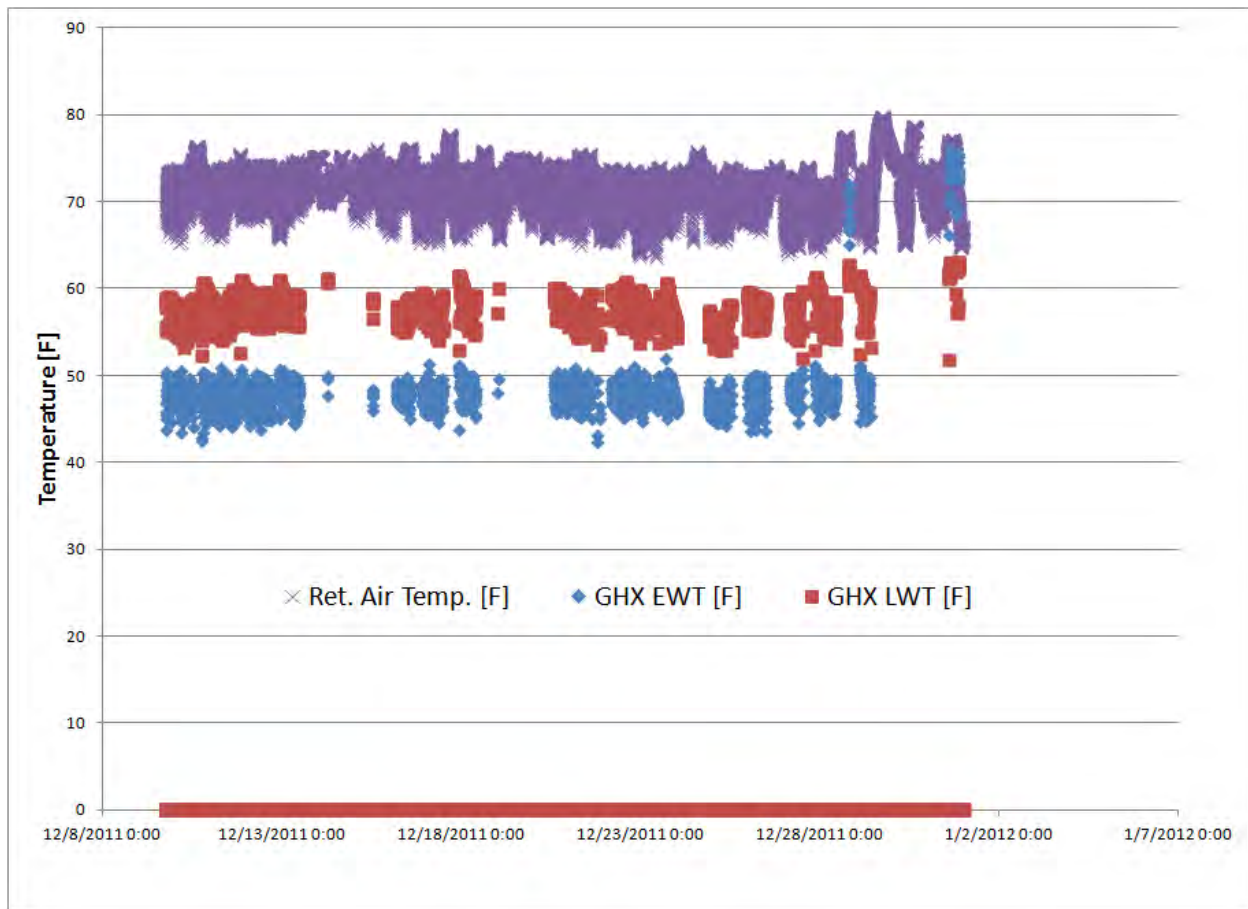


Figure B-1-7-2. Measured room and loop temperatures

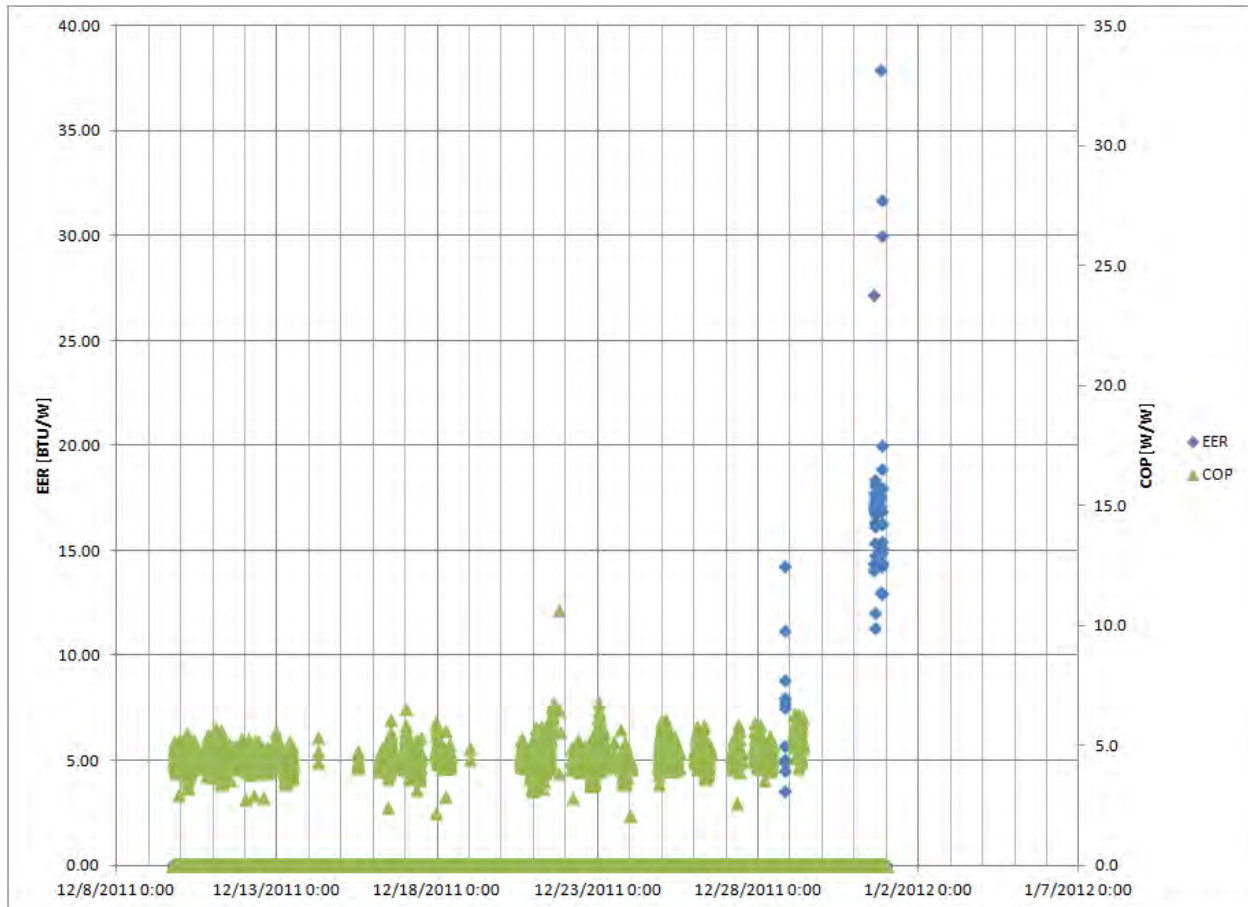


Figure B-1-7-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 08 (829)

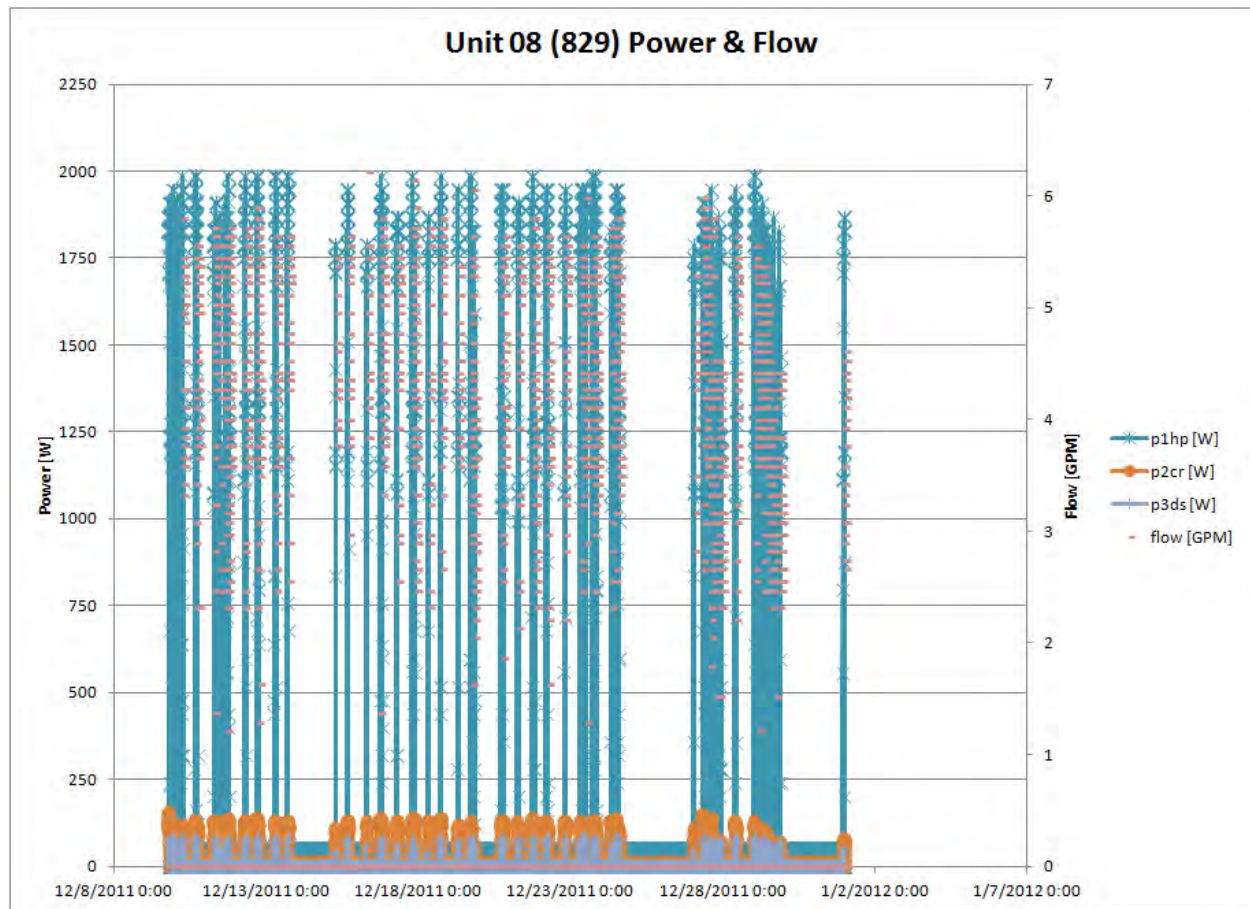


Figure B-1-8-1. Measured power and flow rate

As indicated in the above chart, the heat pump in this home ran most time at full load mode. It is consistent with the profile of the return air temperature as shown in following figure. The return air temperature at the beginning of an operation cycle in this home usually is below 60°F and the operation cycle is ended when the return air temperature reaches around 75°F.

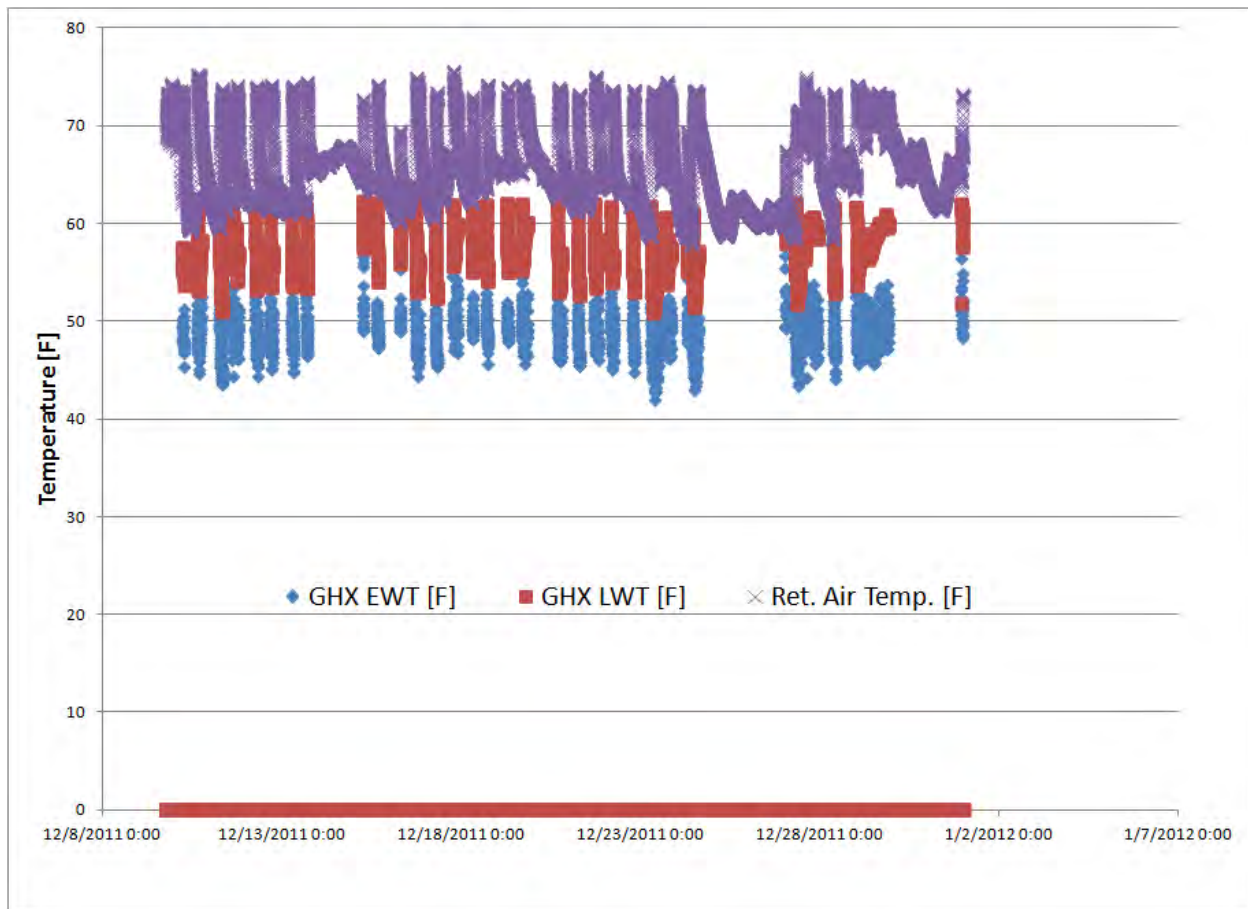


Figure B-1-8-2. Measured room and loop temperatures

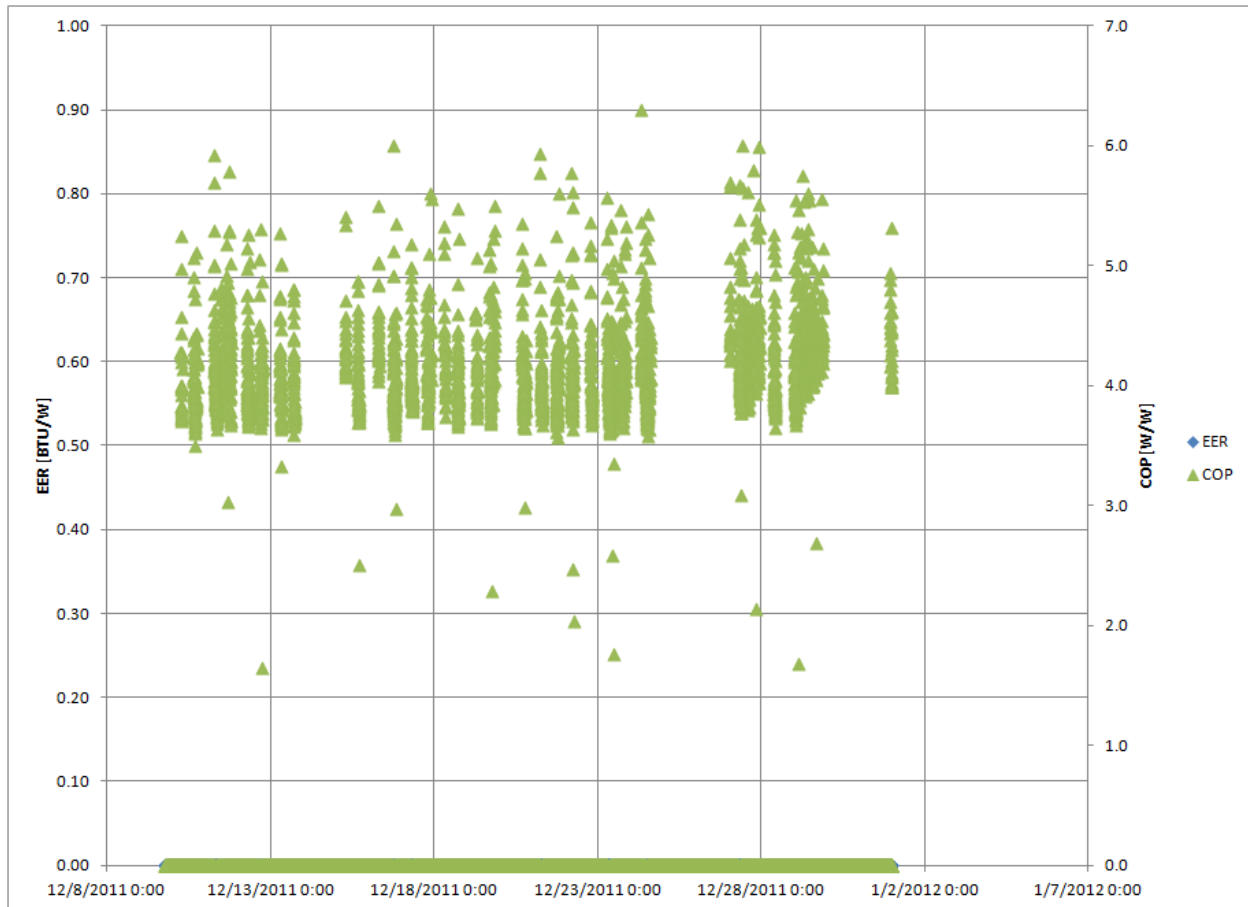


Figure B-1-8-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 09 (944)

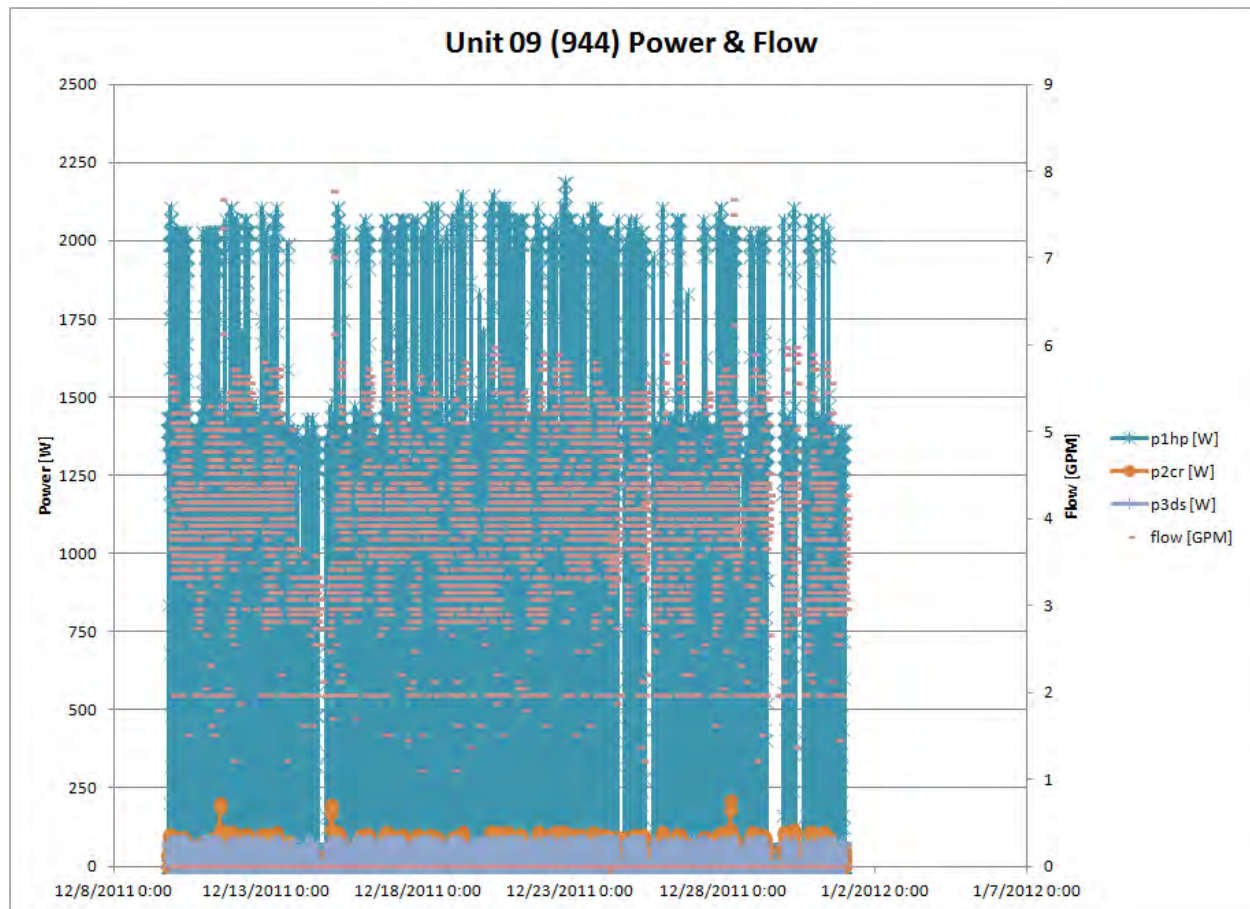


Figure B-1-9-1. Measured power and flow rate

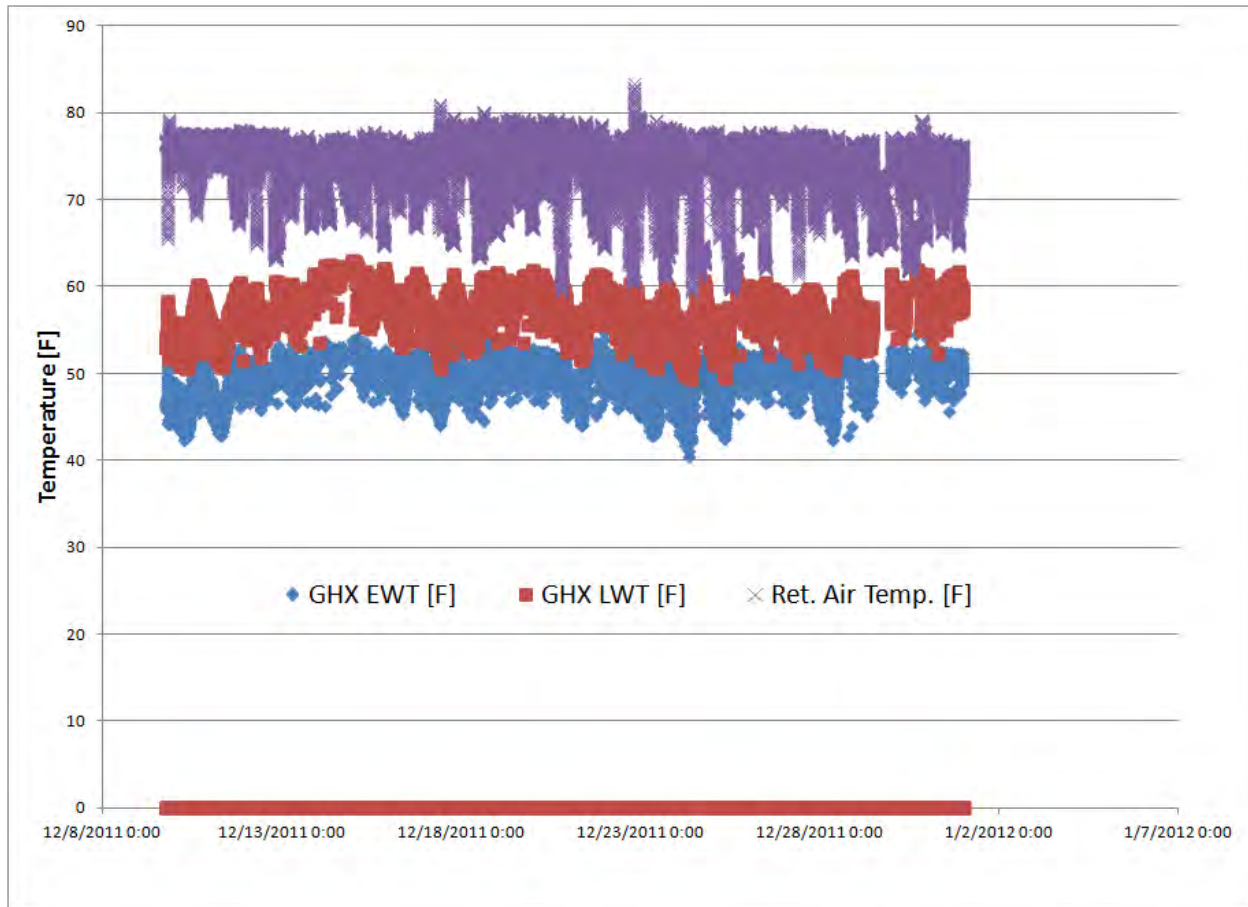


Figure B-1-9-2. Measured room and loop temperatures

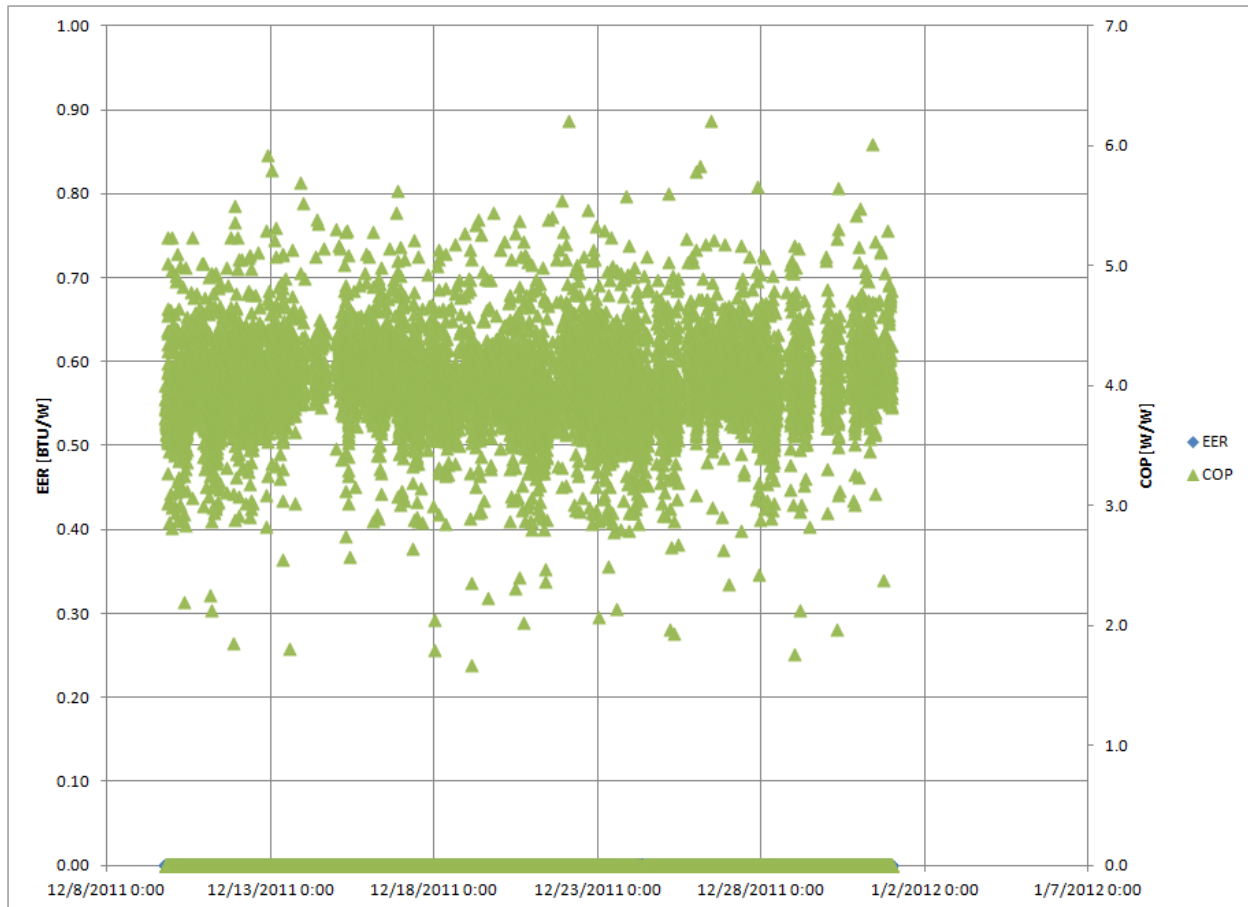


Figure B-1-9-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 10 (8528)

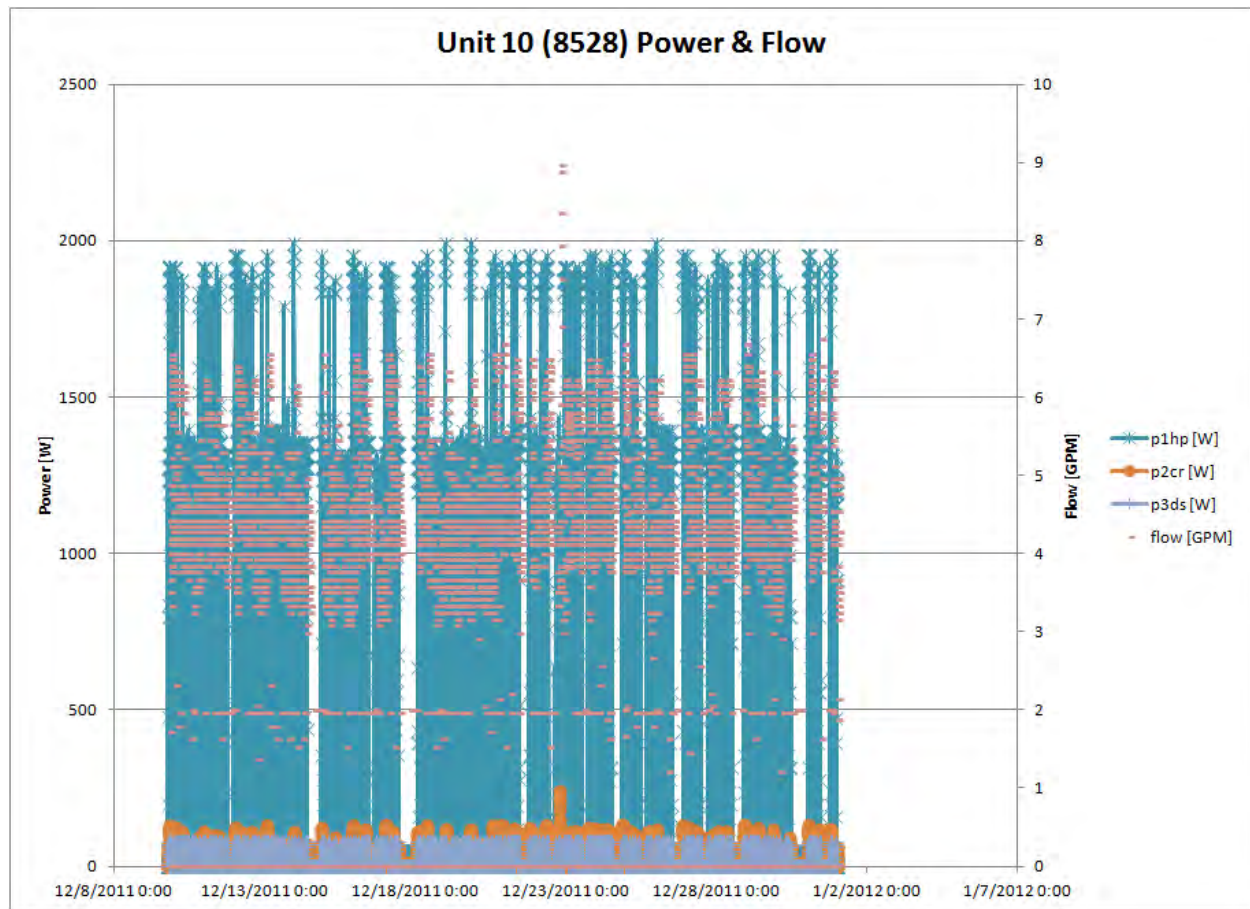


Figure B-1-10-1. Measured power and flow rate

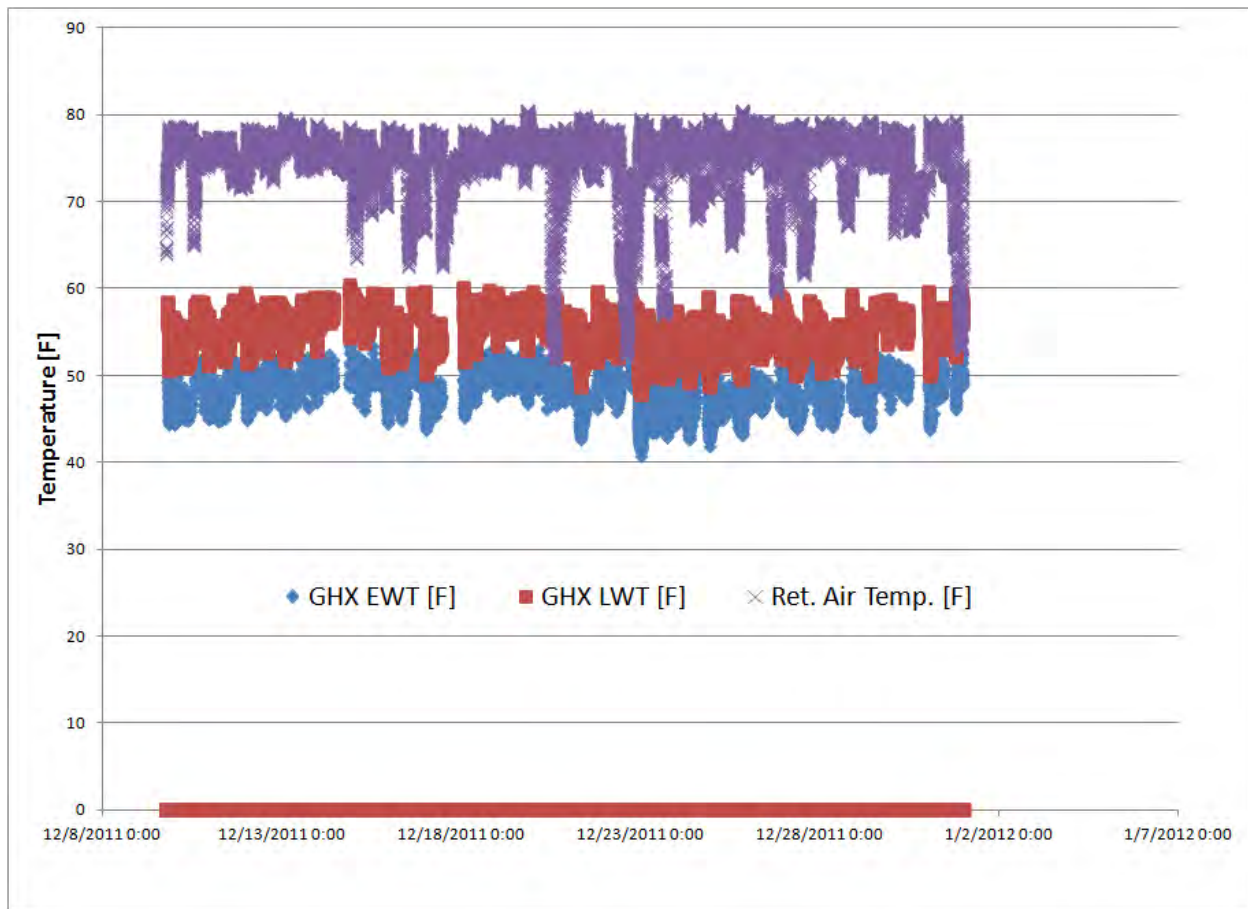


Figure B-1-10-2. Measured room and loop temperatures

The house has the second-highest room temperature set-point (around **79°F**) and the heat pump runs at full-load mode frequently.

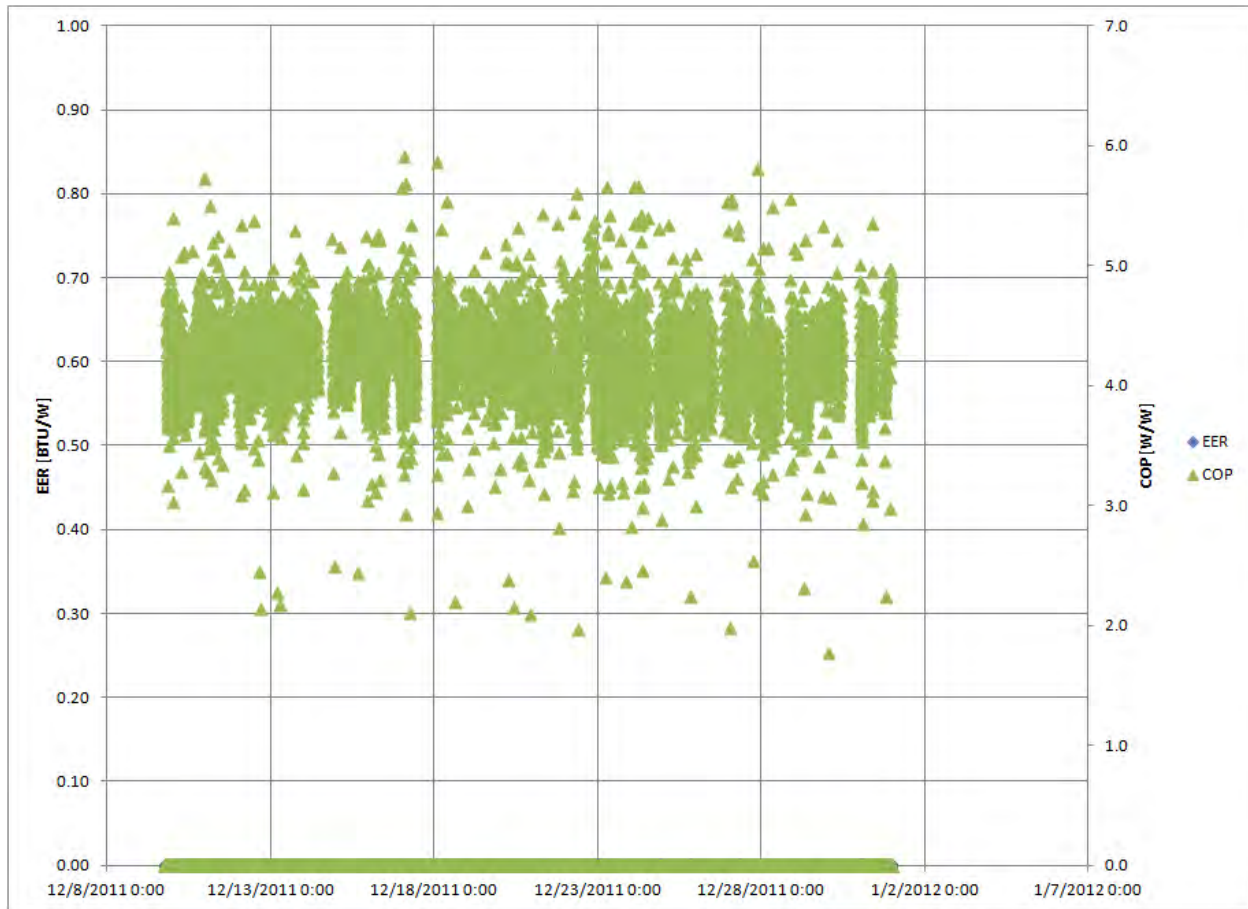


Figure B-1-10-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

B-2: JANUARY 2012

Unit 01 (925)

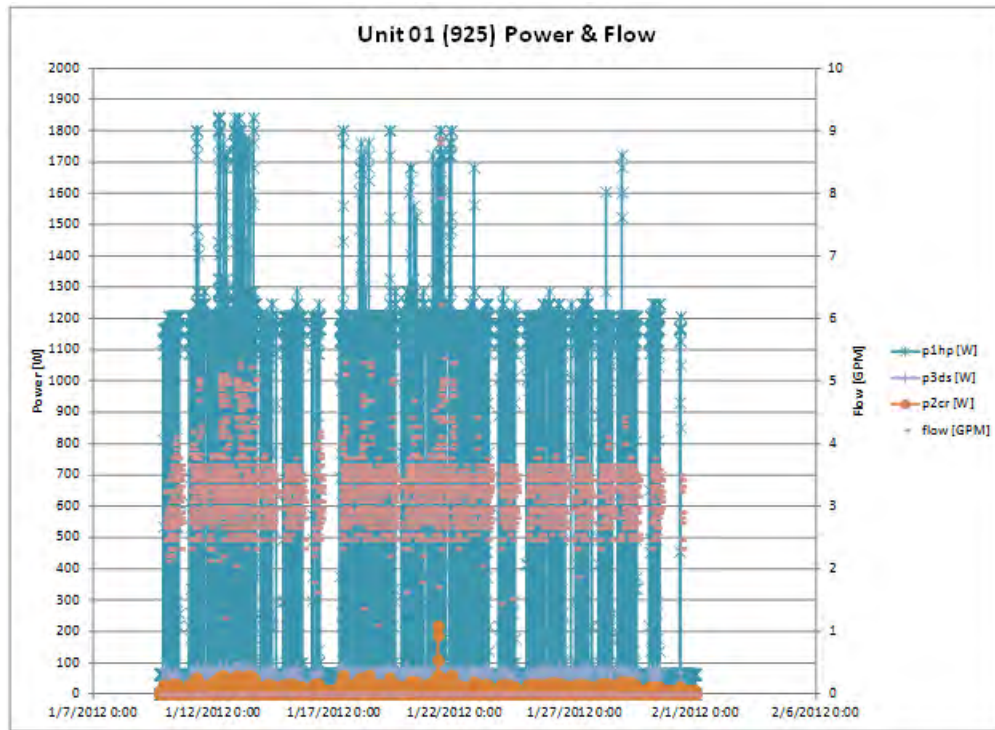


Figure B-2-1-1. Measured power and flow rate

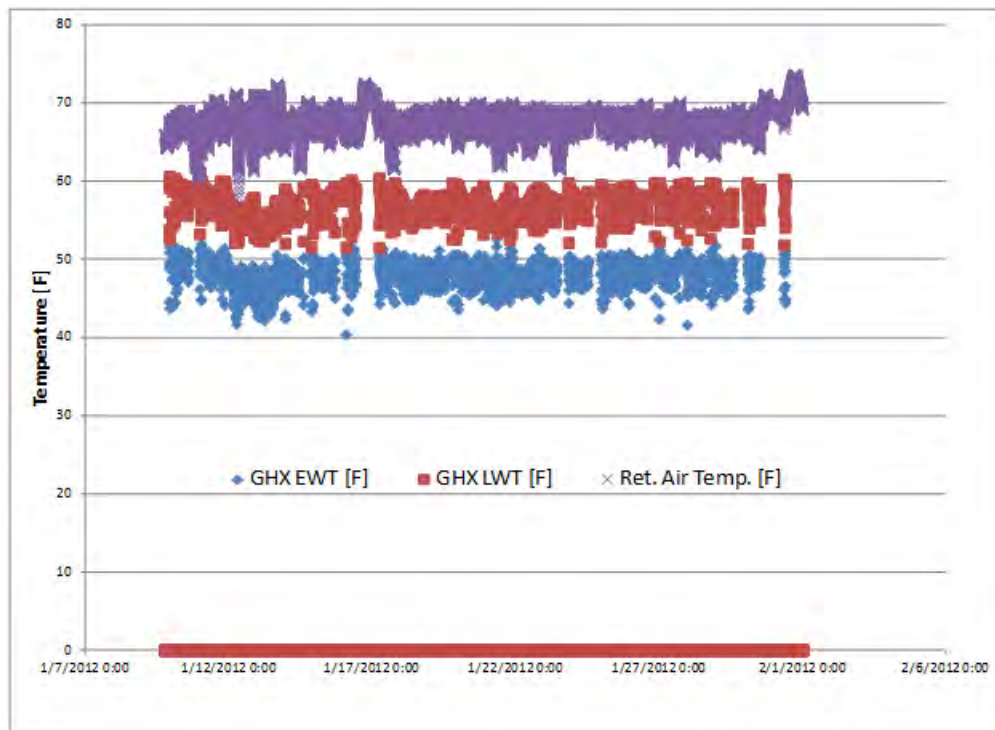


Figure B-2-1-2. Measured room and loop temperatures

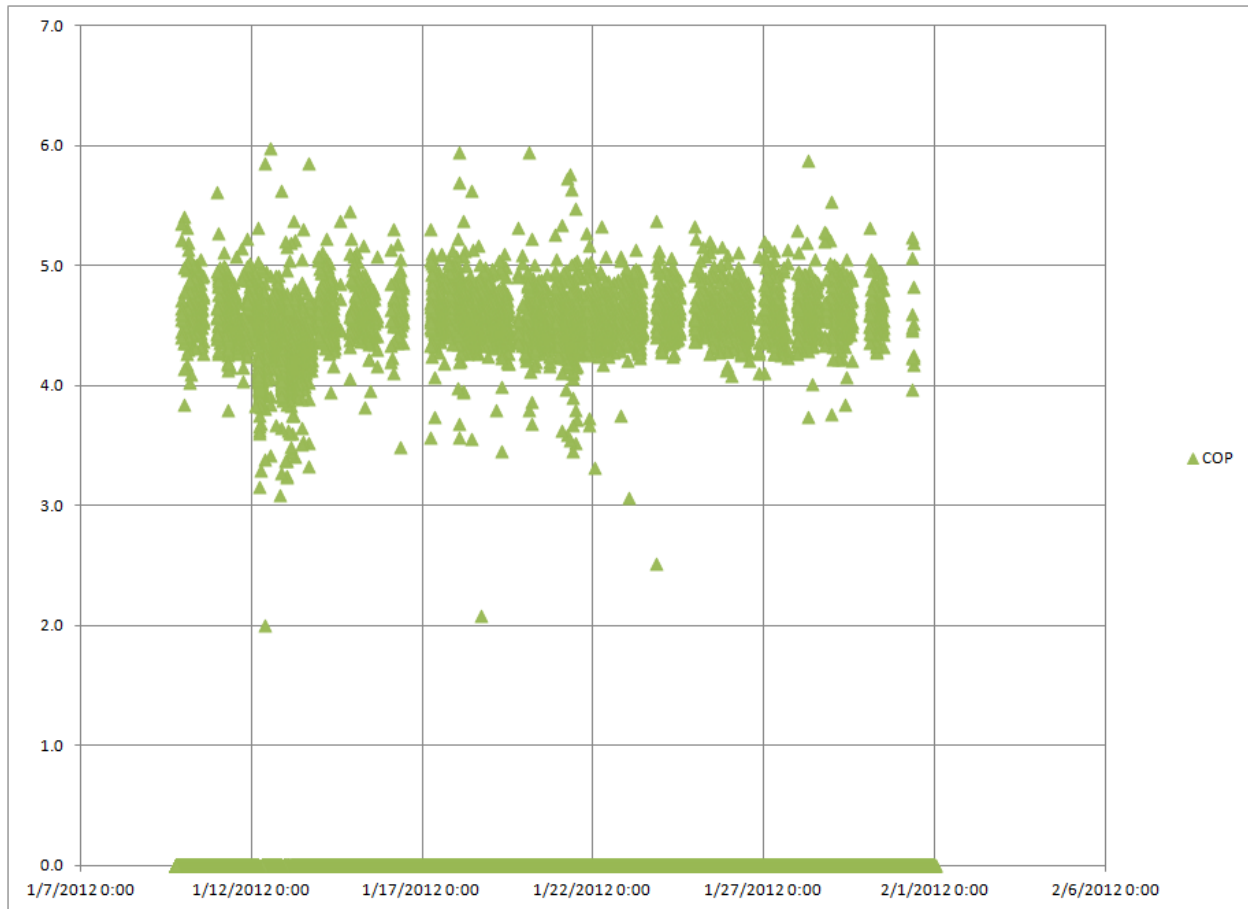


Figure B-2-1-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 02 (916)

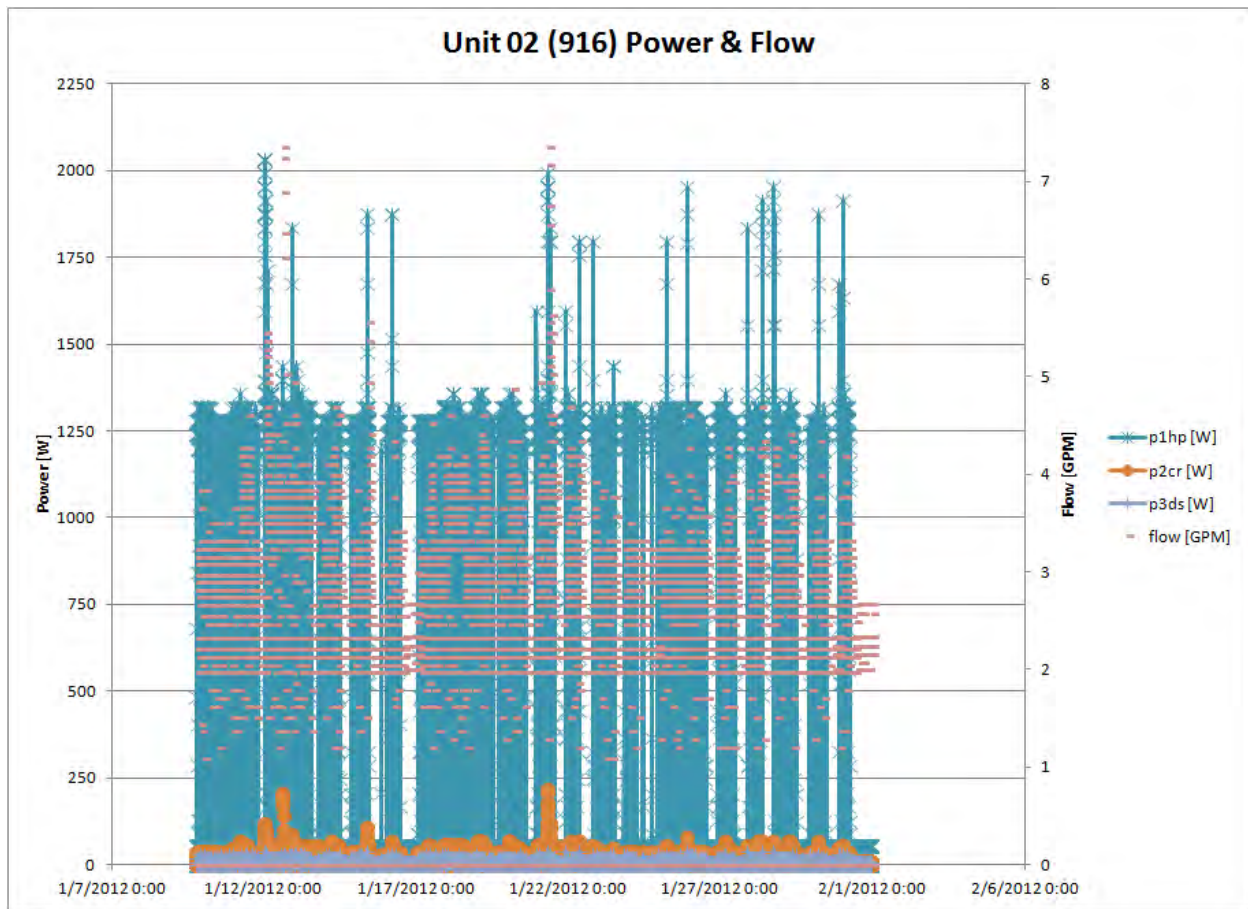


Figure B-2-2-1. Measured power and flow rate

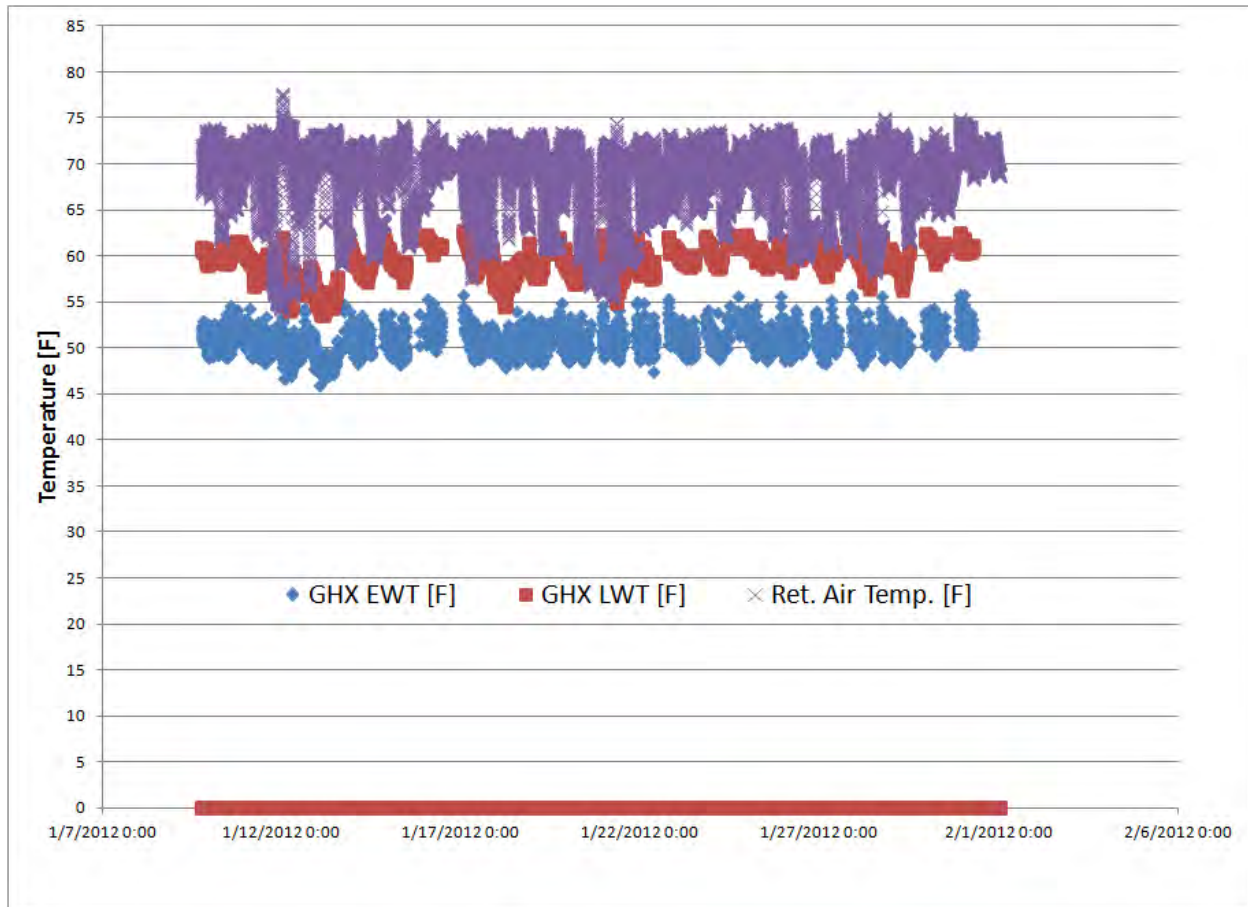


Figure B-2-2-2. Measured room and loop temperatures

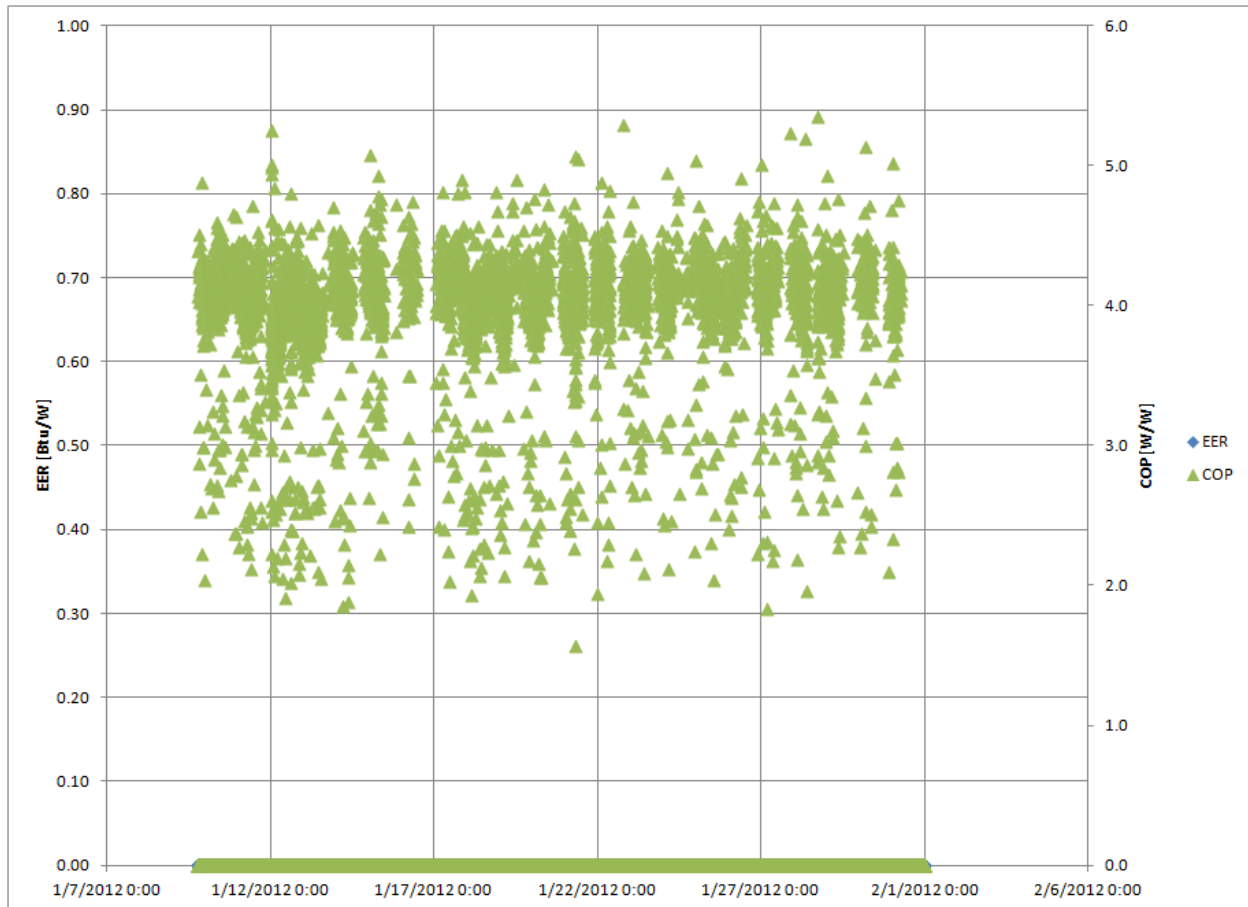


Figure B-2-2-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 03 (833)

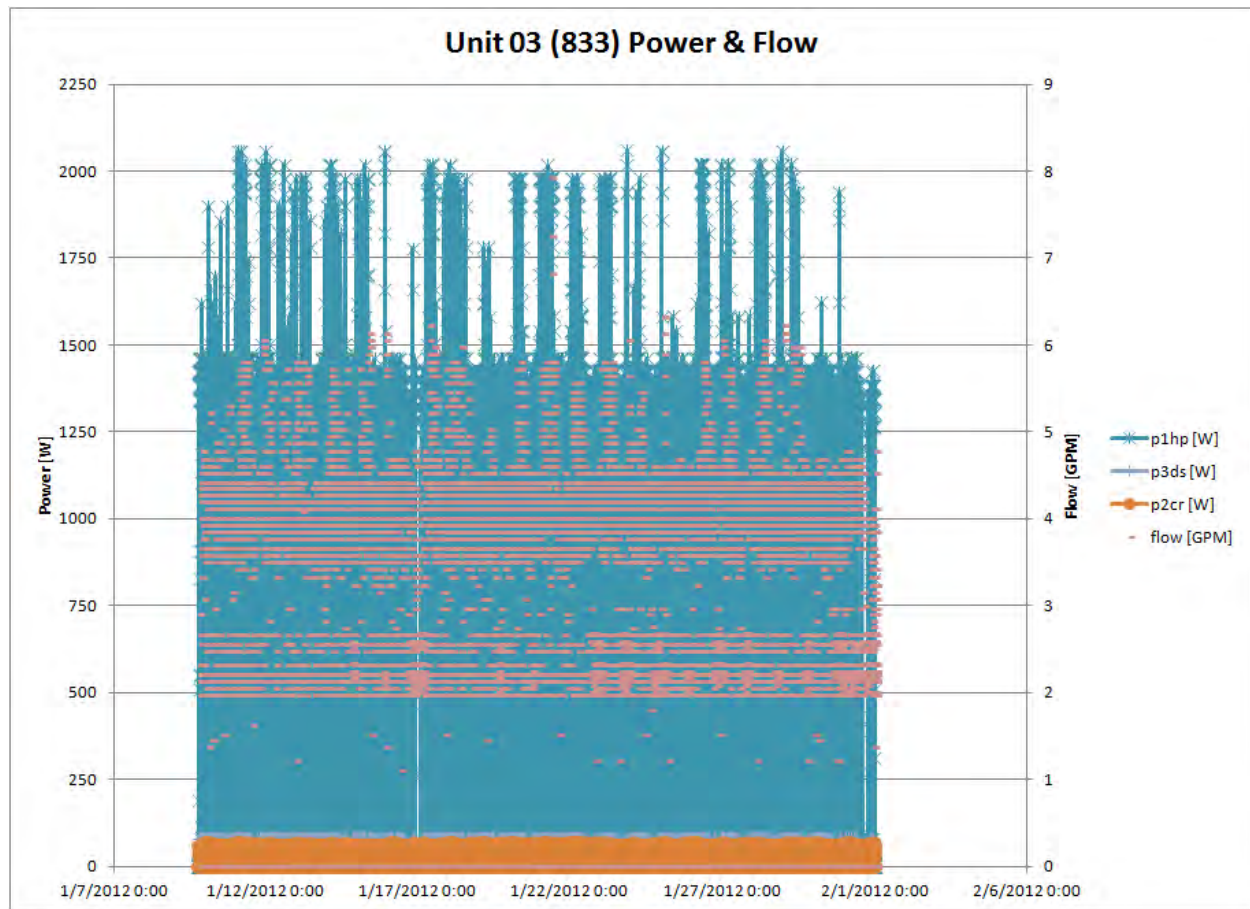


Figure B-2-3-1. Measured power and flow rate

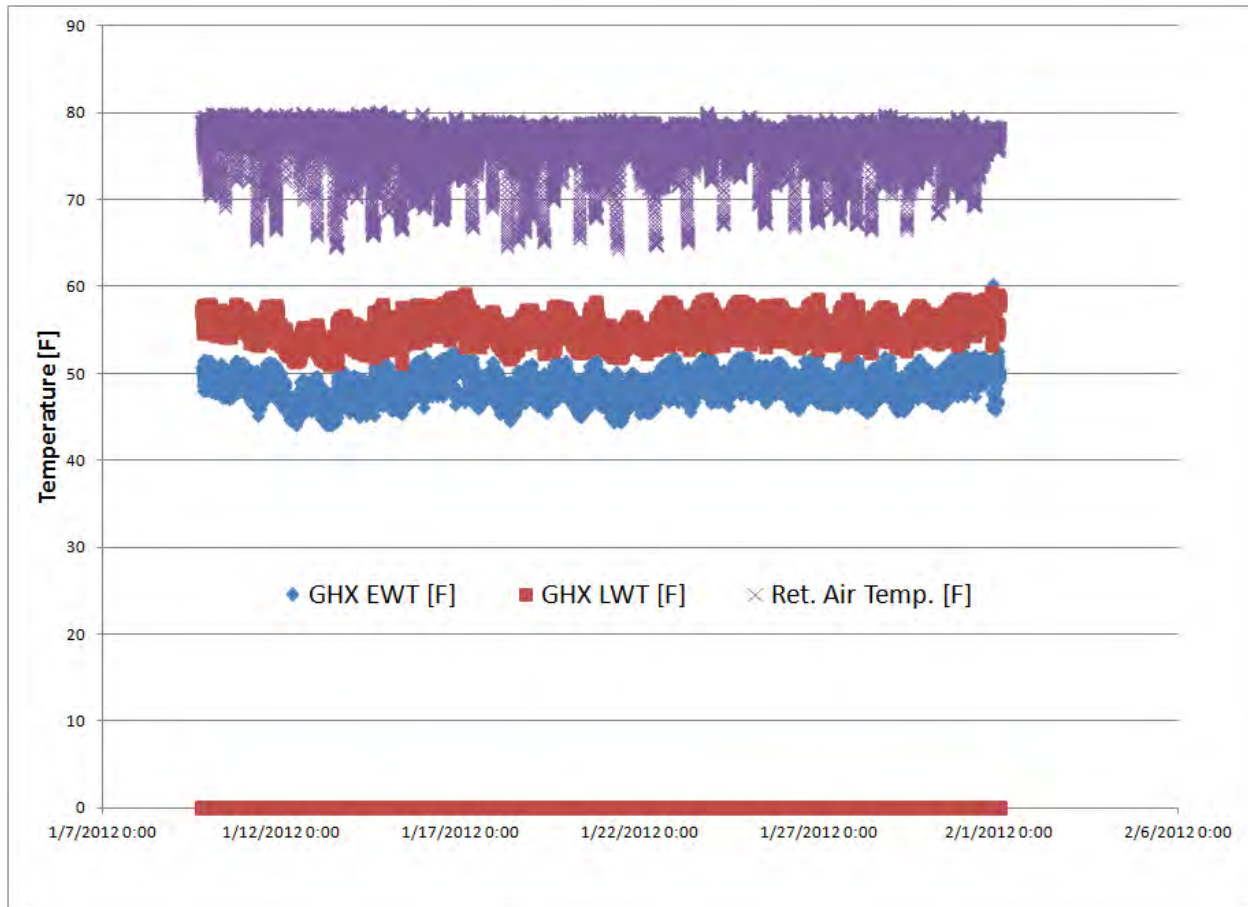


Figure B-2-3-2. Measured room and loop temperatures

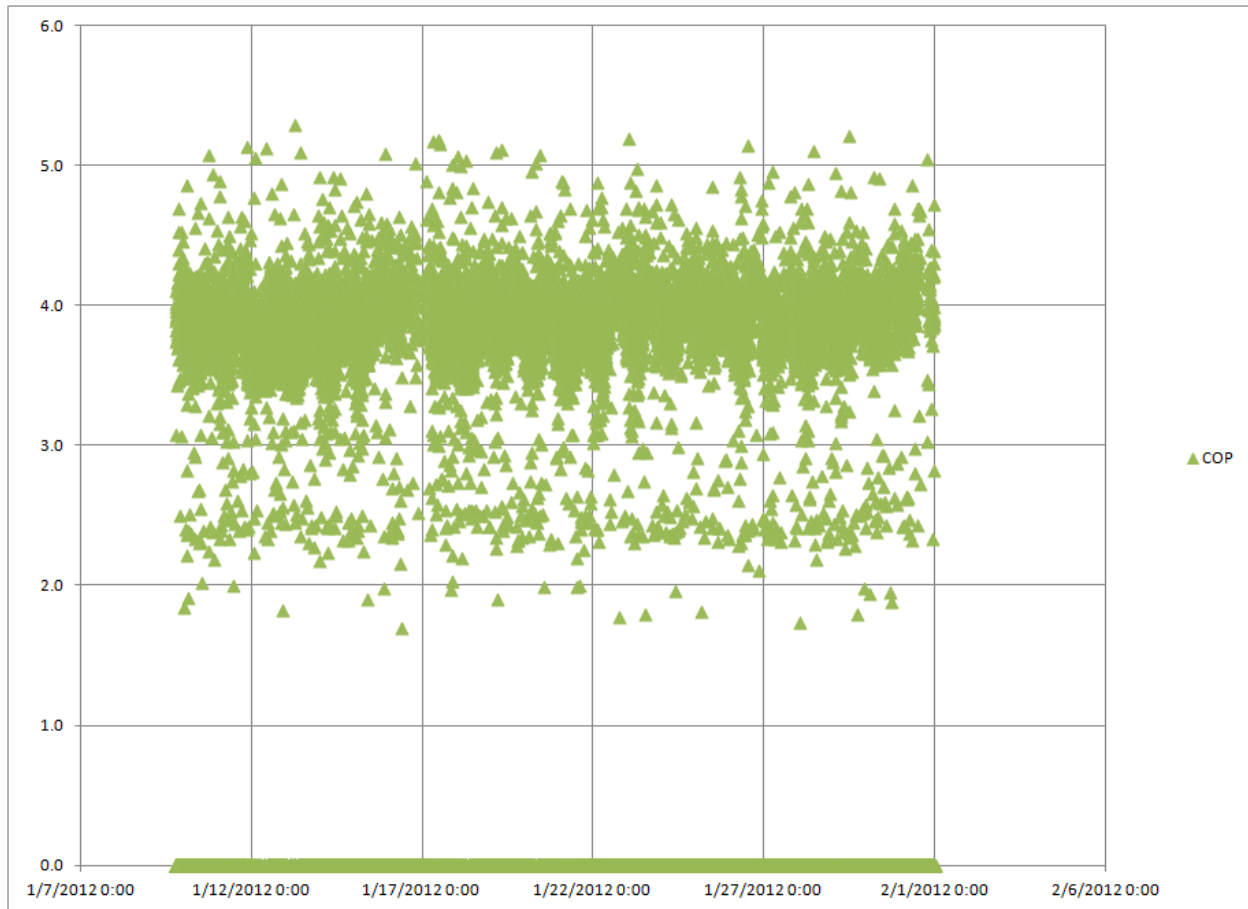


Figure B-2-3-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 04 (932)

The performance data in Unit 04 (932) was missing since late morning on 1/2/2012 due to a hard disk failure in the data acquisition system. The only available 2-days worthy data are shown in this session, which presents a close-up look at the operation and performance of the GSHP system.

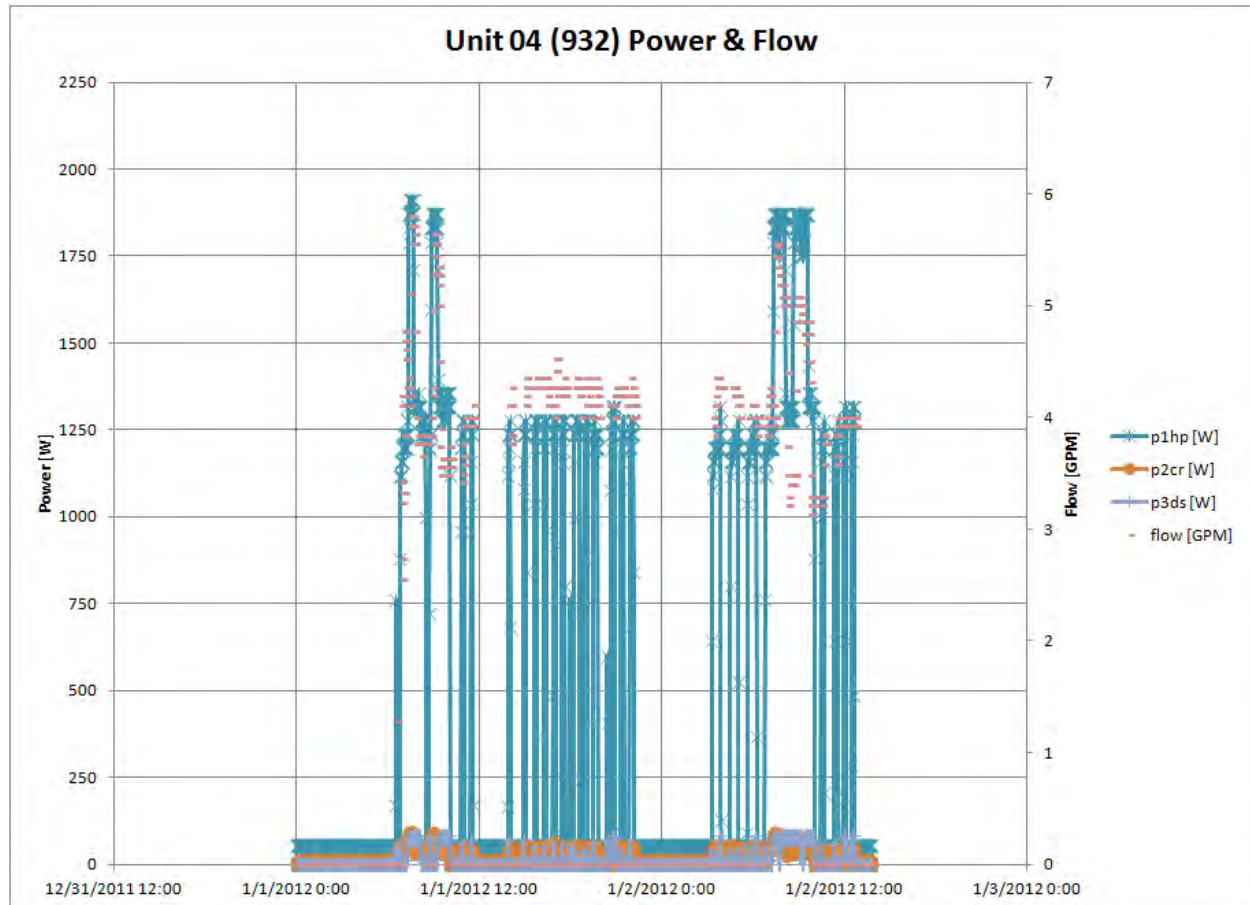


Figure B-2-4-1. Measured power and flow rate

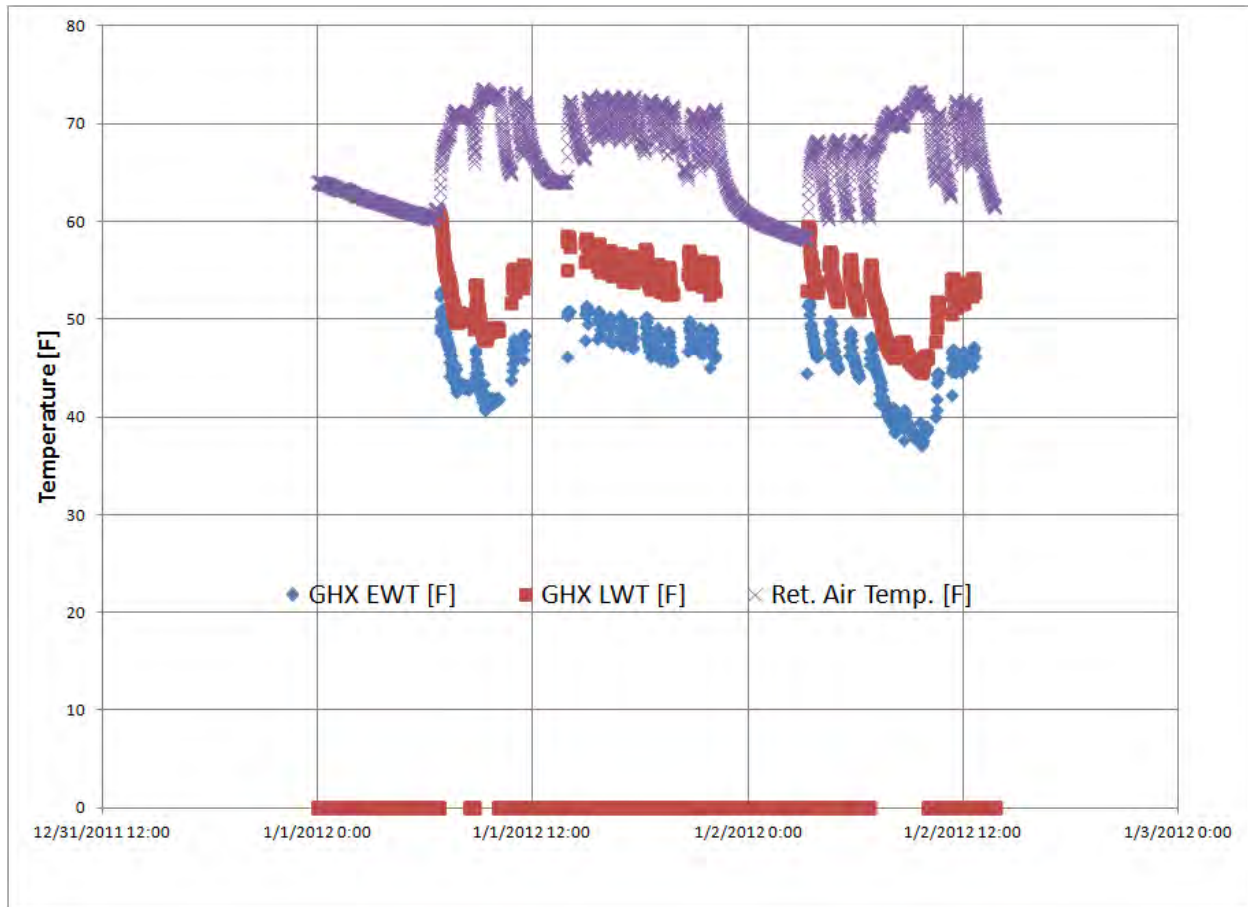


Figure B-2-4-2. Measured room and loop temperatures

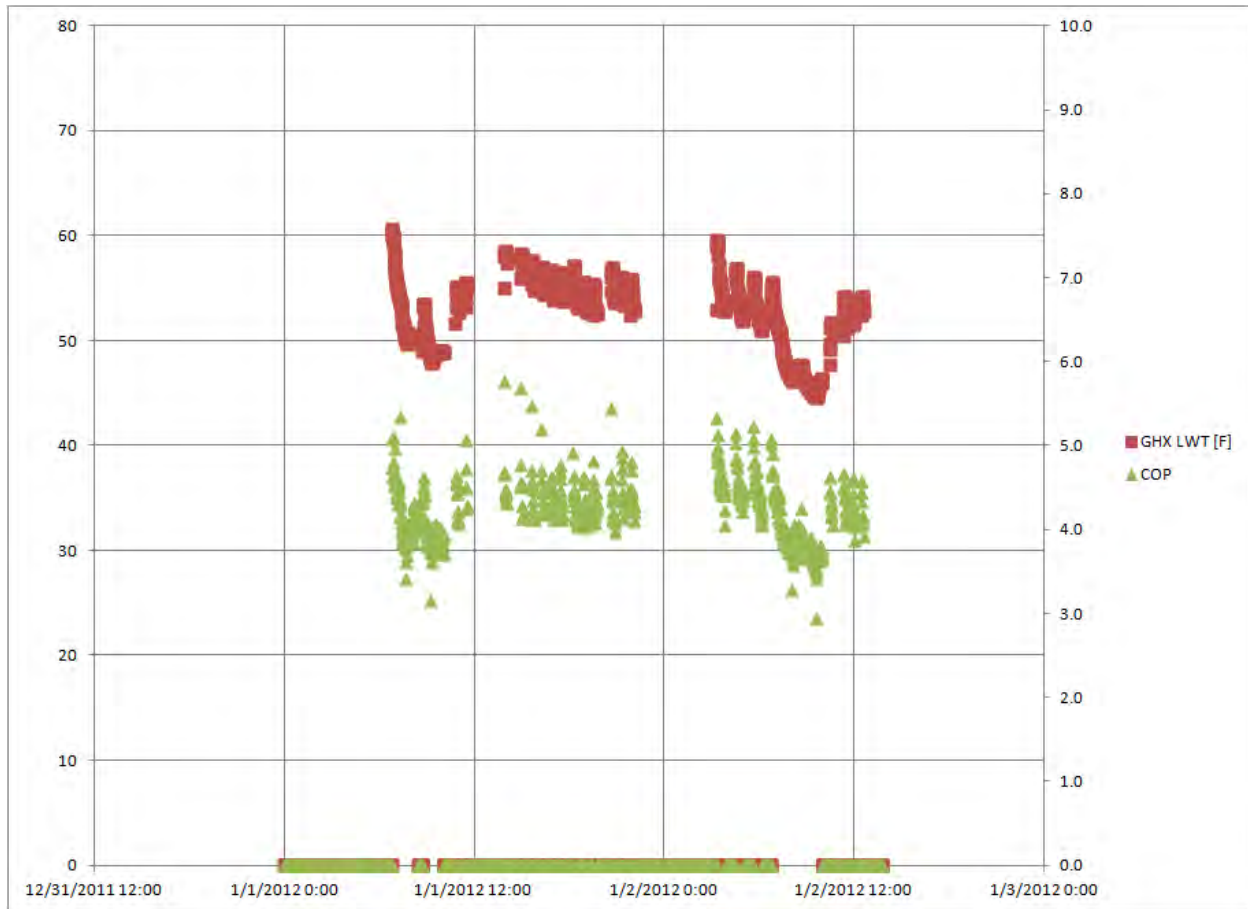


Figure B-2-4-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 05 (813)

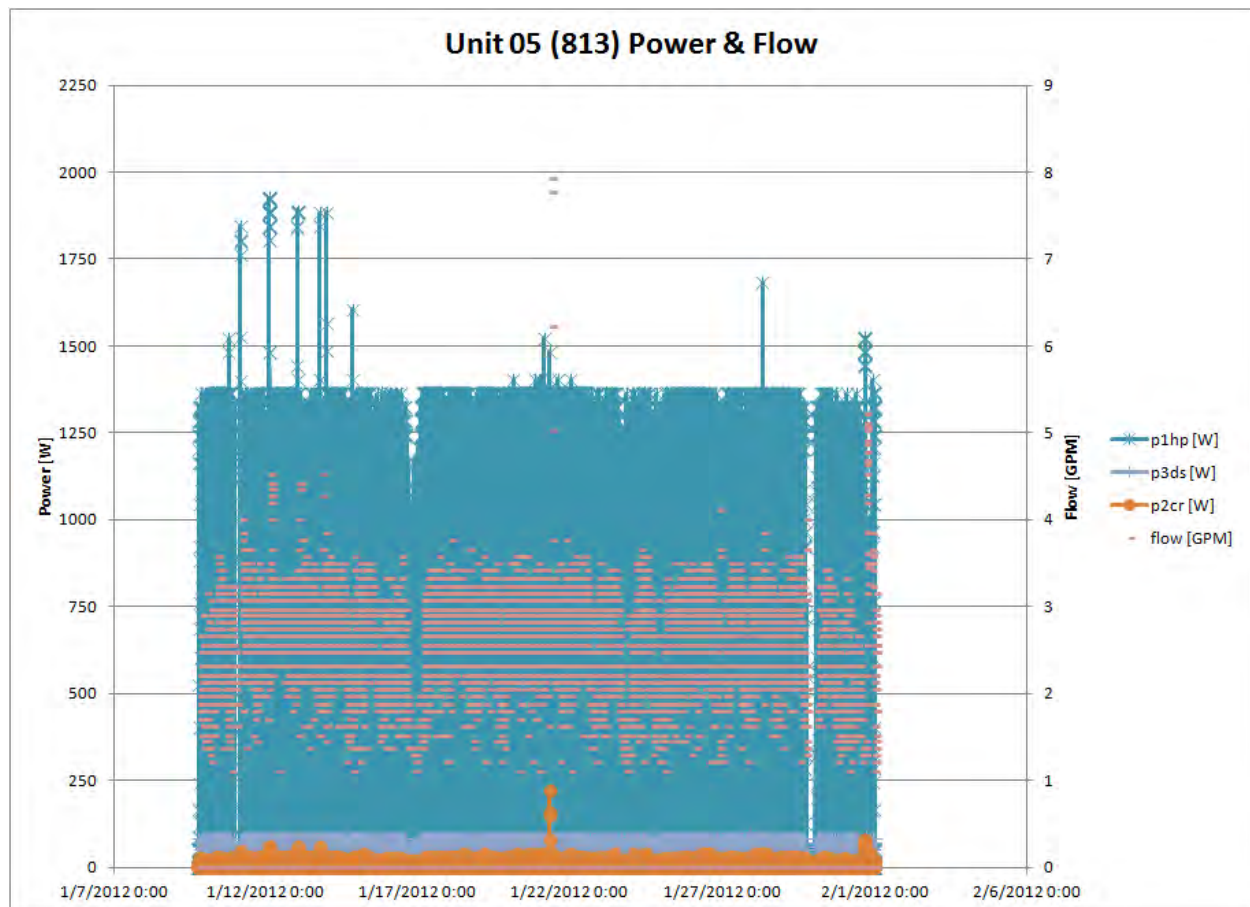


Figure B-2-5-1. Measured power and flow rate

This home has a high room temperature set-point (around 78.5°F) and the room temperature (measured at the return air duct) did not fluctuate in large range as it was observed in other homes. It indicated that the thermostat was set up to run the GHP system (or the fan) continuously and the room temperature was maintained near constant all the time. At the end of January, the GHP system was even run in cooling mode to maintain the room temperature set point. The monthly average COP at this home is relatively lower (4.0) than that of Unit 01 (4.5) while the monthly average loop LFTs were about the same in these two homes (56.7F vs. 56.8F).

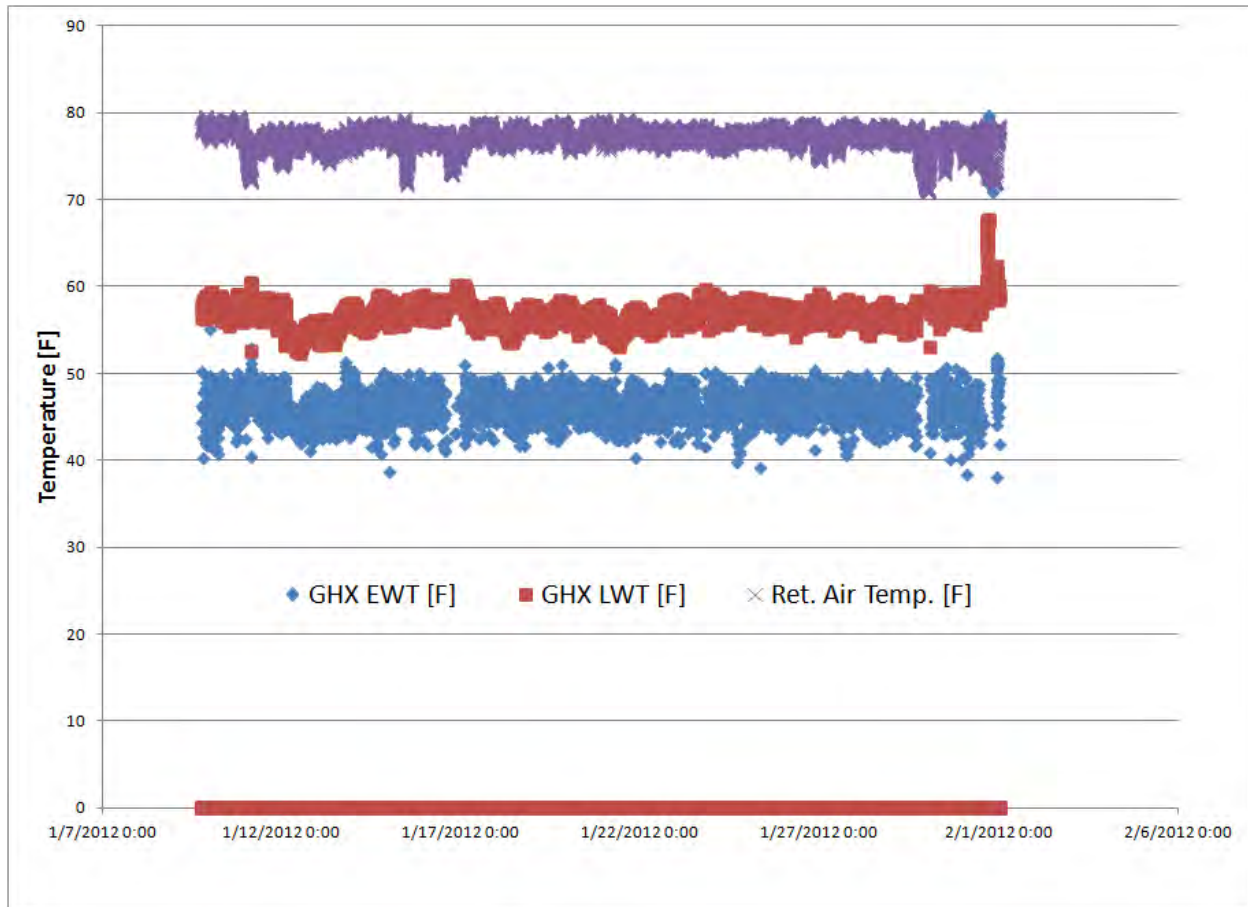


Figure B-2-5-2. Measured room and loop temperatures

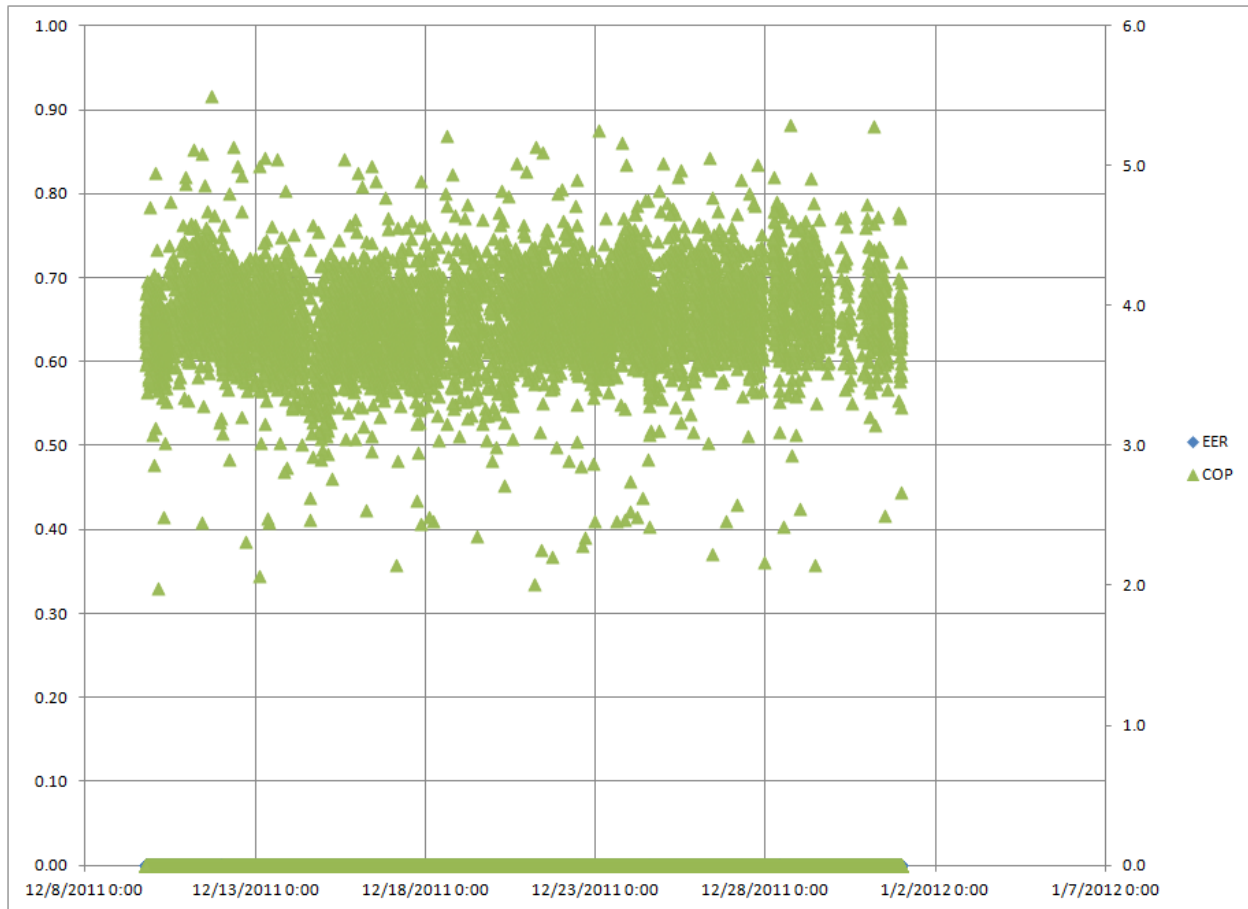


Figure B-2-5-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 06 (824)

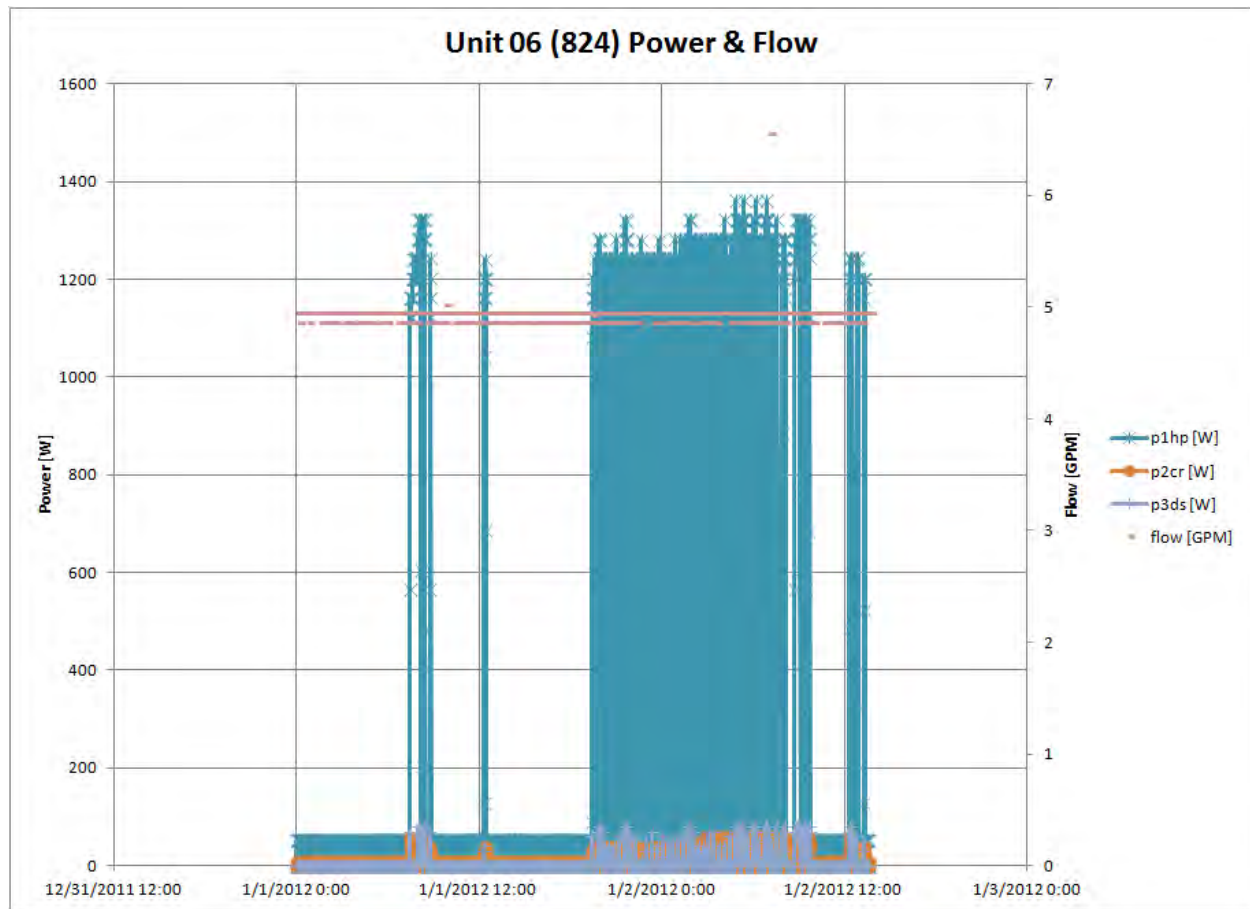


Figure B-2-6-1. Measured power and flow rate

The flow rate measurements showed constant flow at 4.95 GPM, but the power measurement of the circulator was not consistent with it. Also, the heating/cooling capacity determined from ground heat transfer rate is not consistent with the heat pump power measurement. It indicates that the flow rate measurement is not accurate and the EER/COP calculated using the flow rate measurements are not valid.

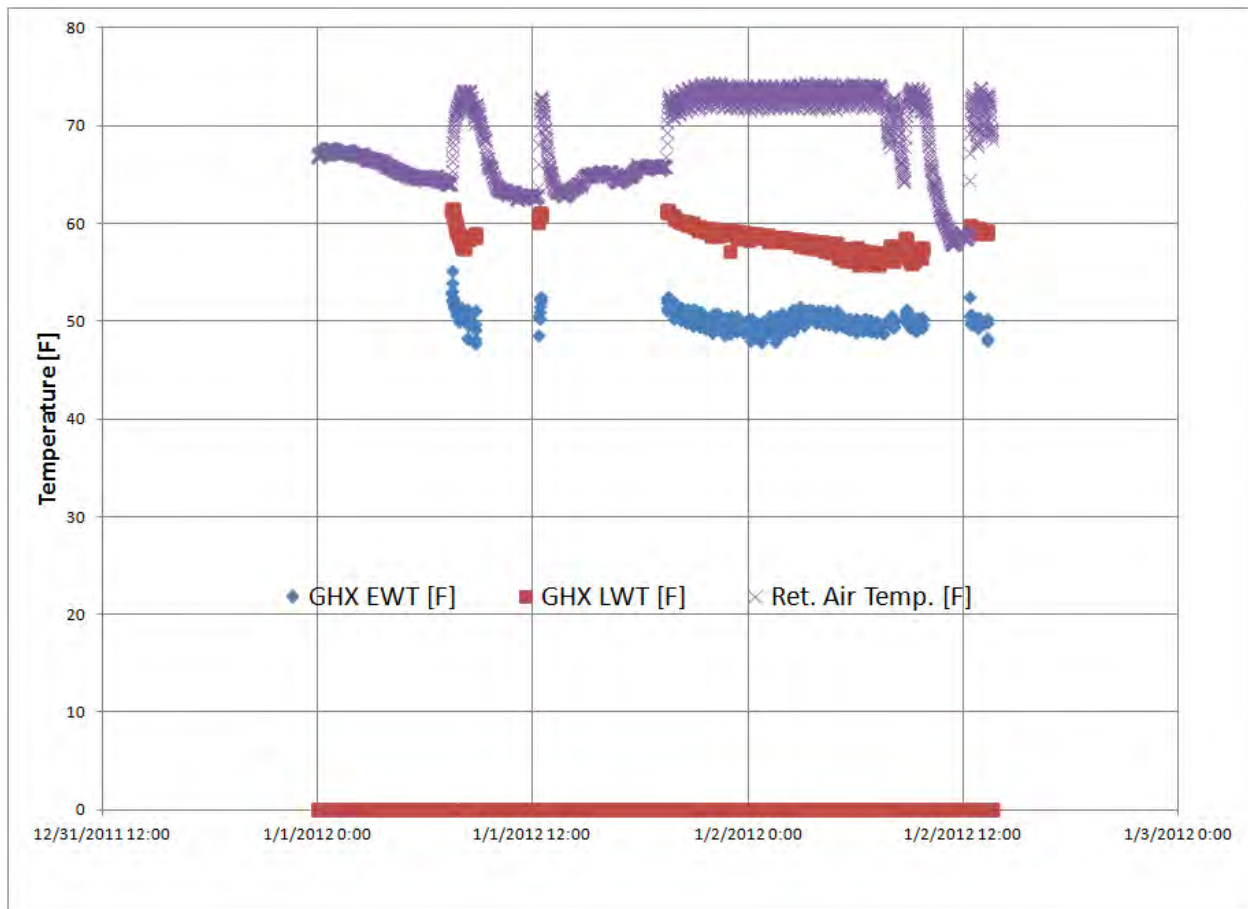


Figure B-2-6-2. Measured room and loop temperatures

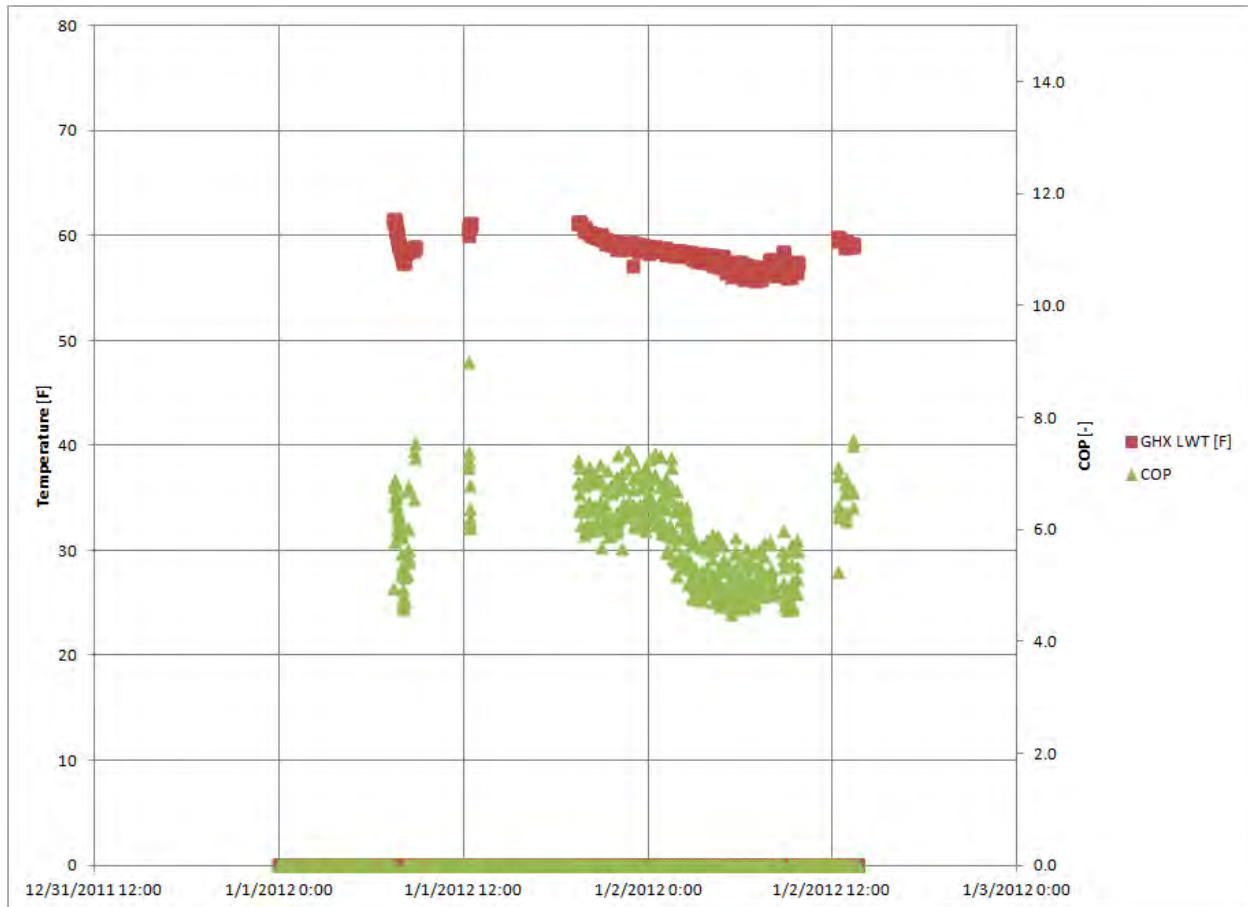


Figure B-2-6-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

The high COP is due to the inaccurate flow rate measurements.

Unit 07 (928)

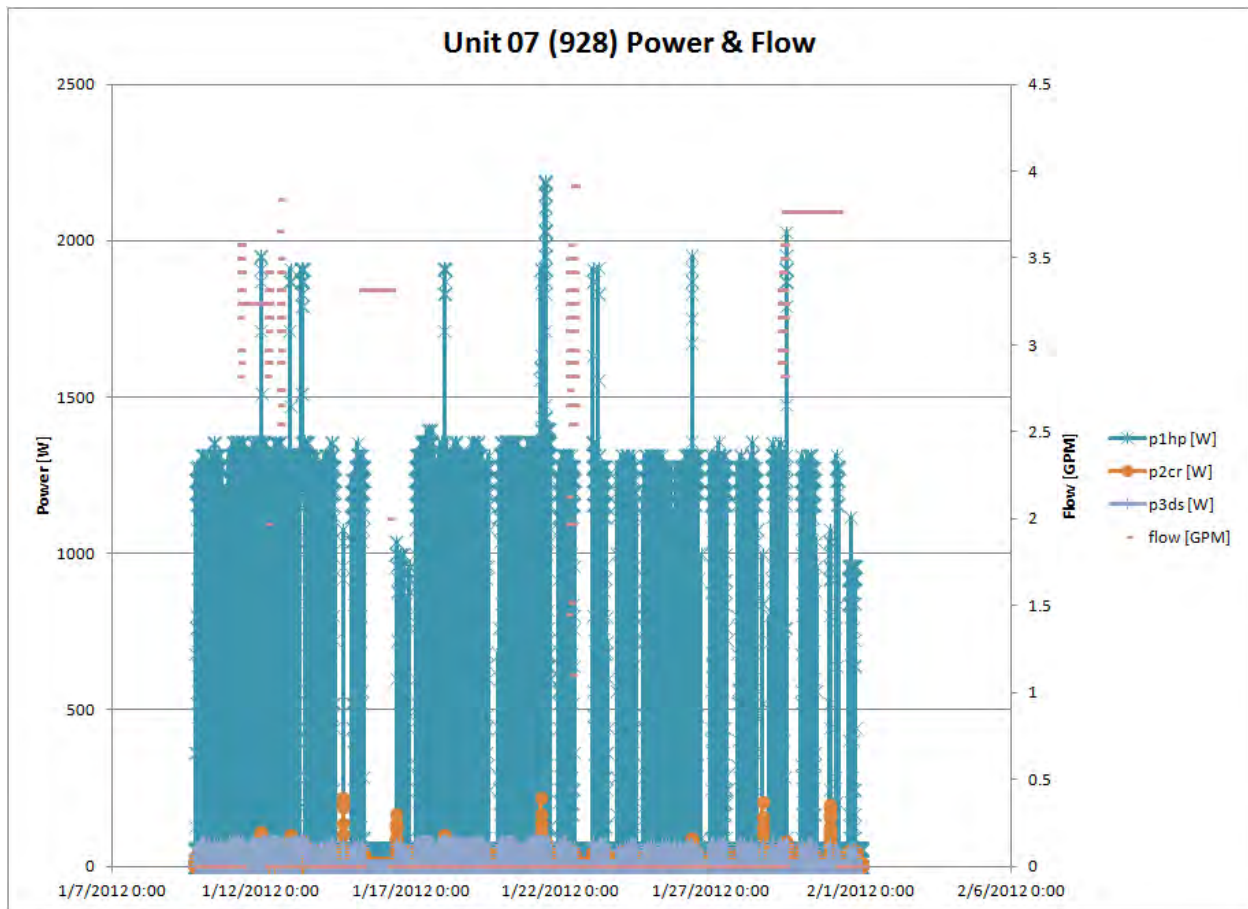


Figure B-2-7-1. Measured power and flow rate

The above chart indicates that flow data was missing during most time of this month.

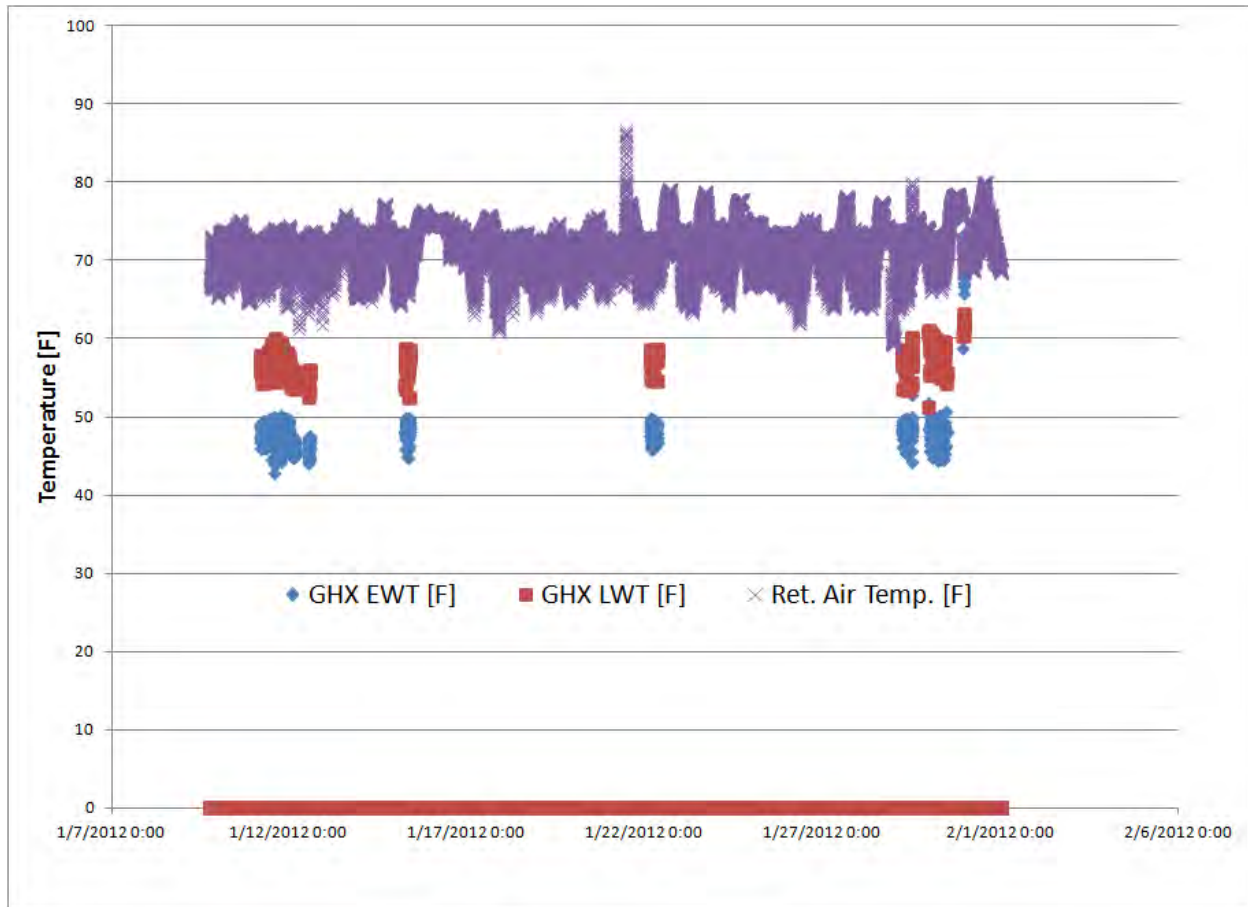


Figure B-2-7-2. Measured room and loop temperatures

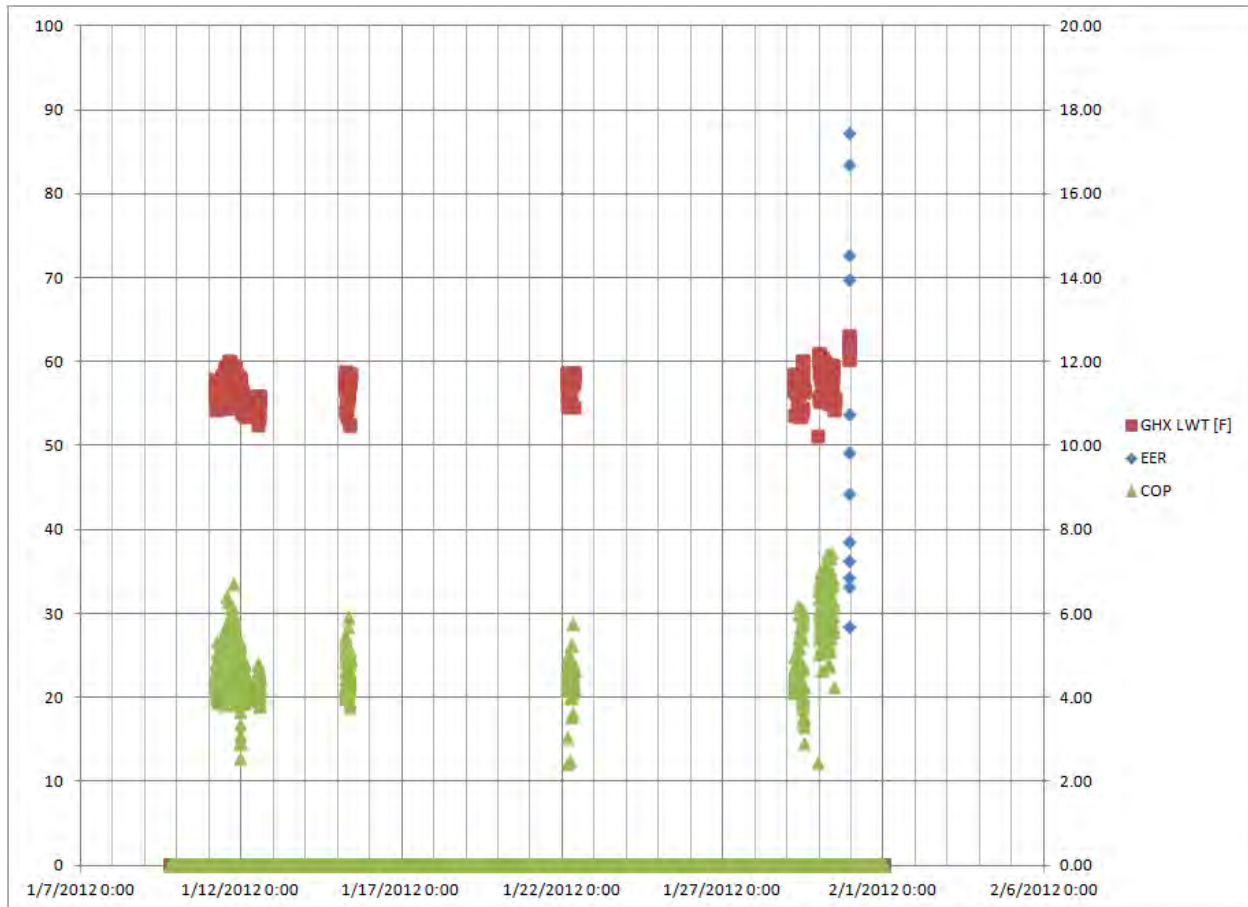


Figure B-2-7-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

The above chart shows data only when the flow rate data is available during this month.

Unit 08 (829)

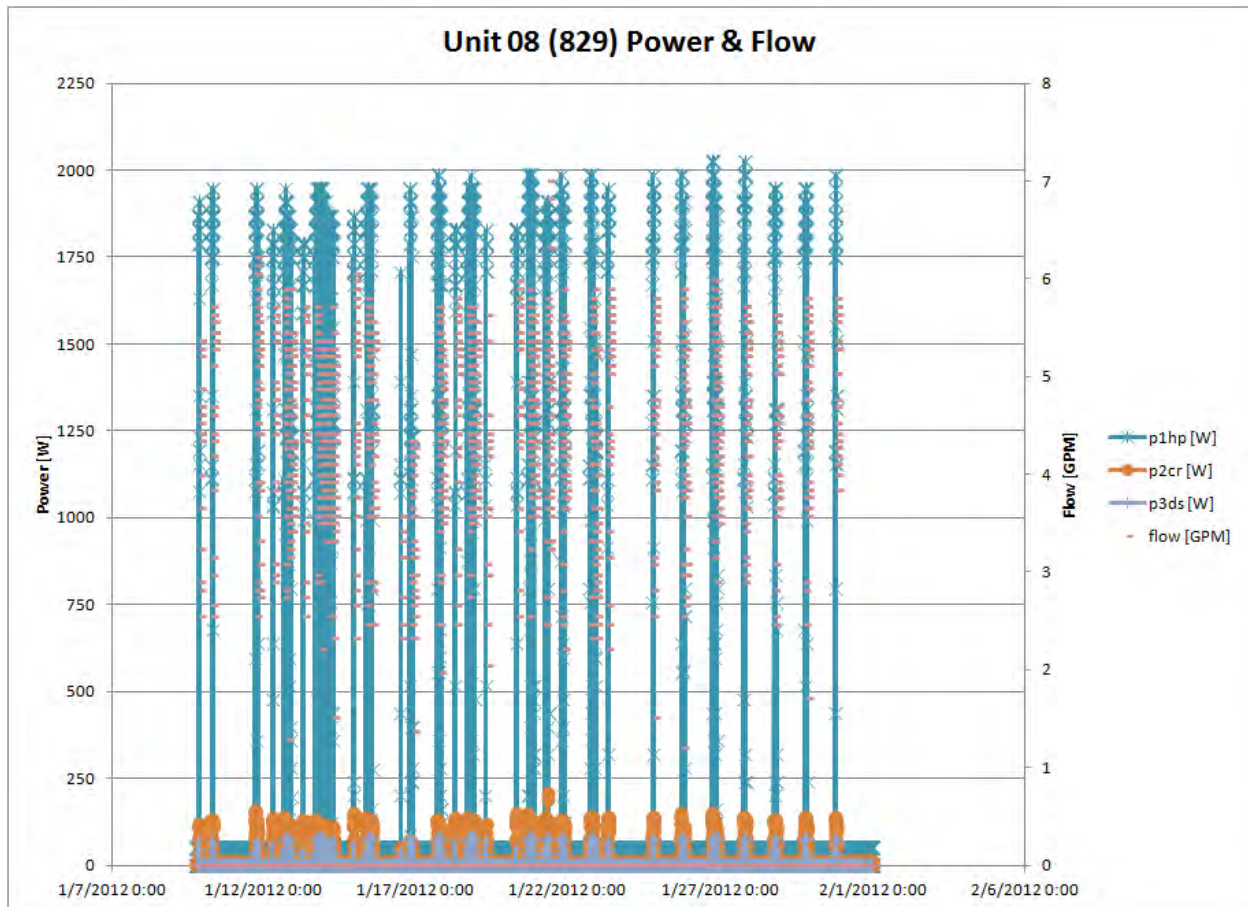


Figure B-2-8-1. Measured power and flow rate

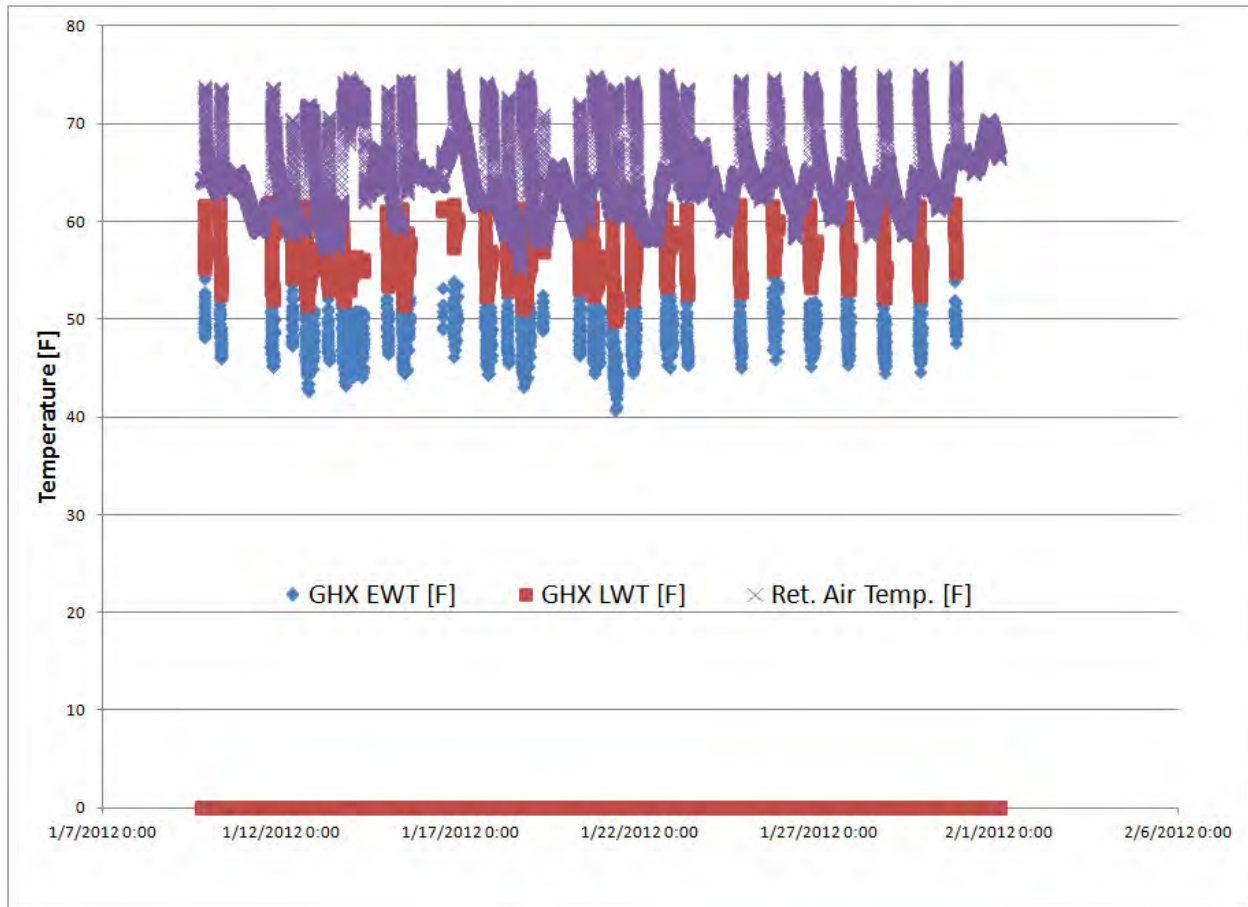


Figure B-2-8-2. Measured room and loop temperatures

The above chart indicates that the GHP system was turned on only at certain time during a day and there were big differences between the room temperature and the thermostat set point when the heat pump was turned on. As a result, the heat pump ran at full-load mode much more frequently than other homes.

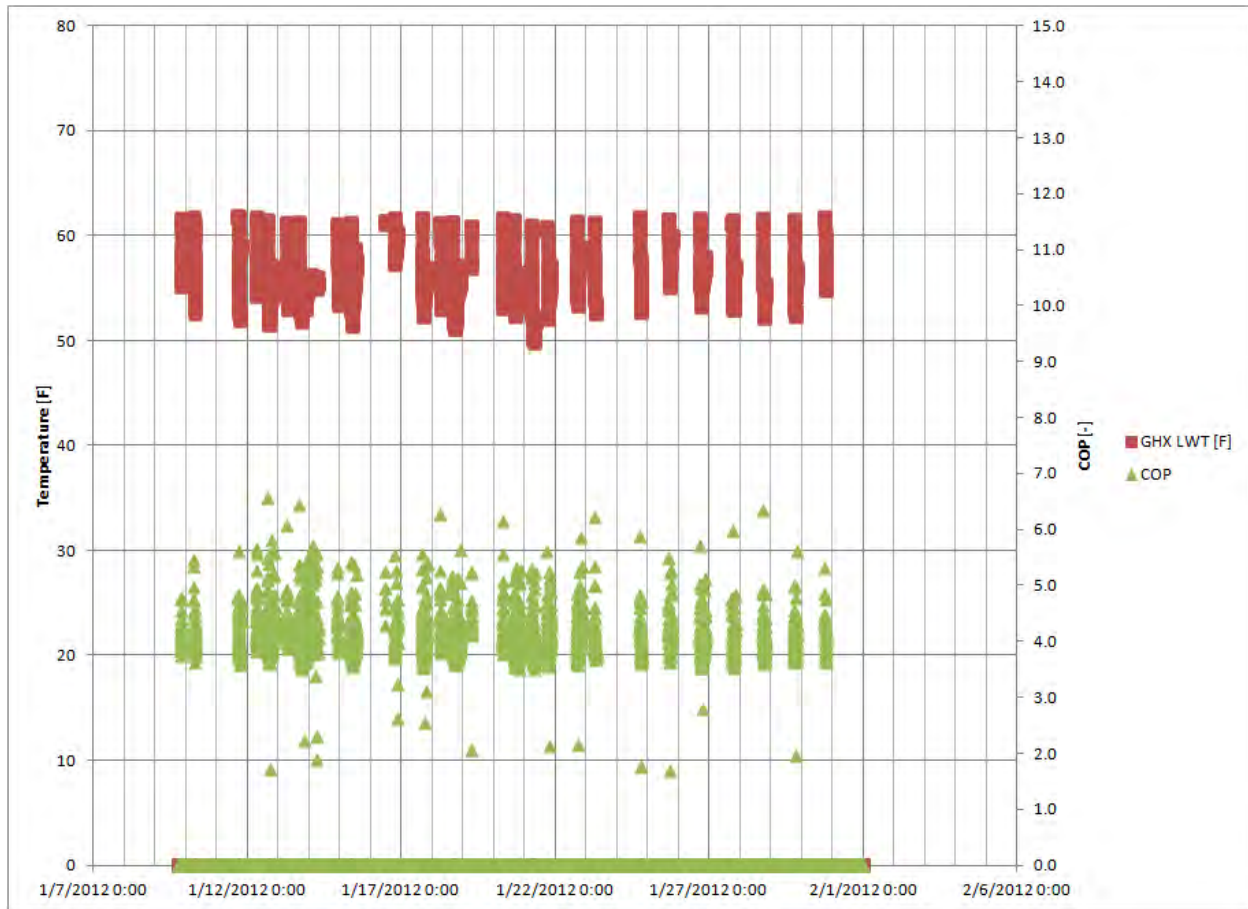


Figure B-2-8-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 09 (944)

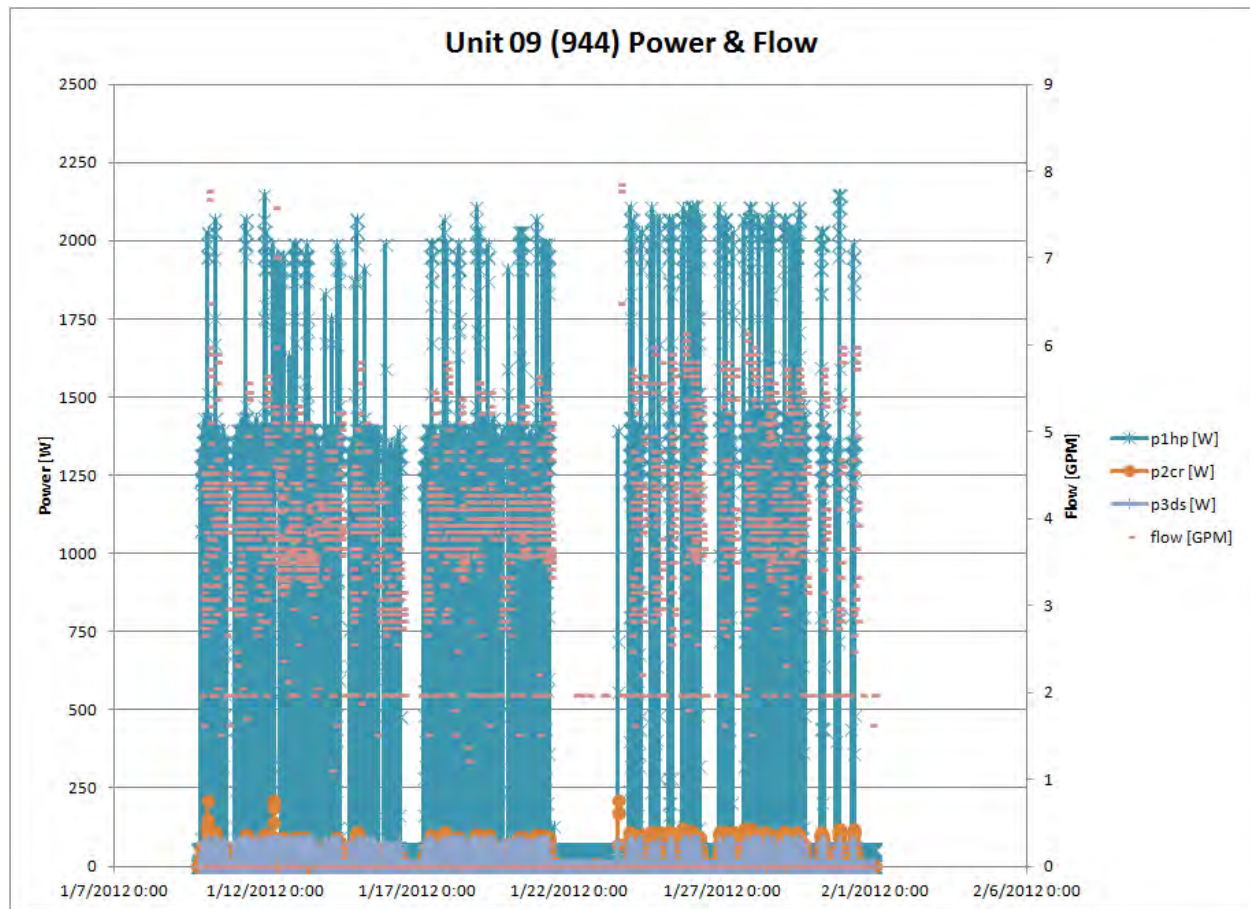


Figure B-2-9-1. Measured power and flow rate



Figure B-2-9-2. Measured room and loop temperatures

The above chart showed that the thermostat set-point was about **75.5°F** before 1/21/2012 and then it was increased to about **78.5°F** since 1/23/2012. The heat pump ran at full-load mode frequently in this month. The above two charts indicated that the GHP system was turned off from 1/21/2012 around 10 am for about 2 days.

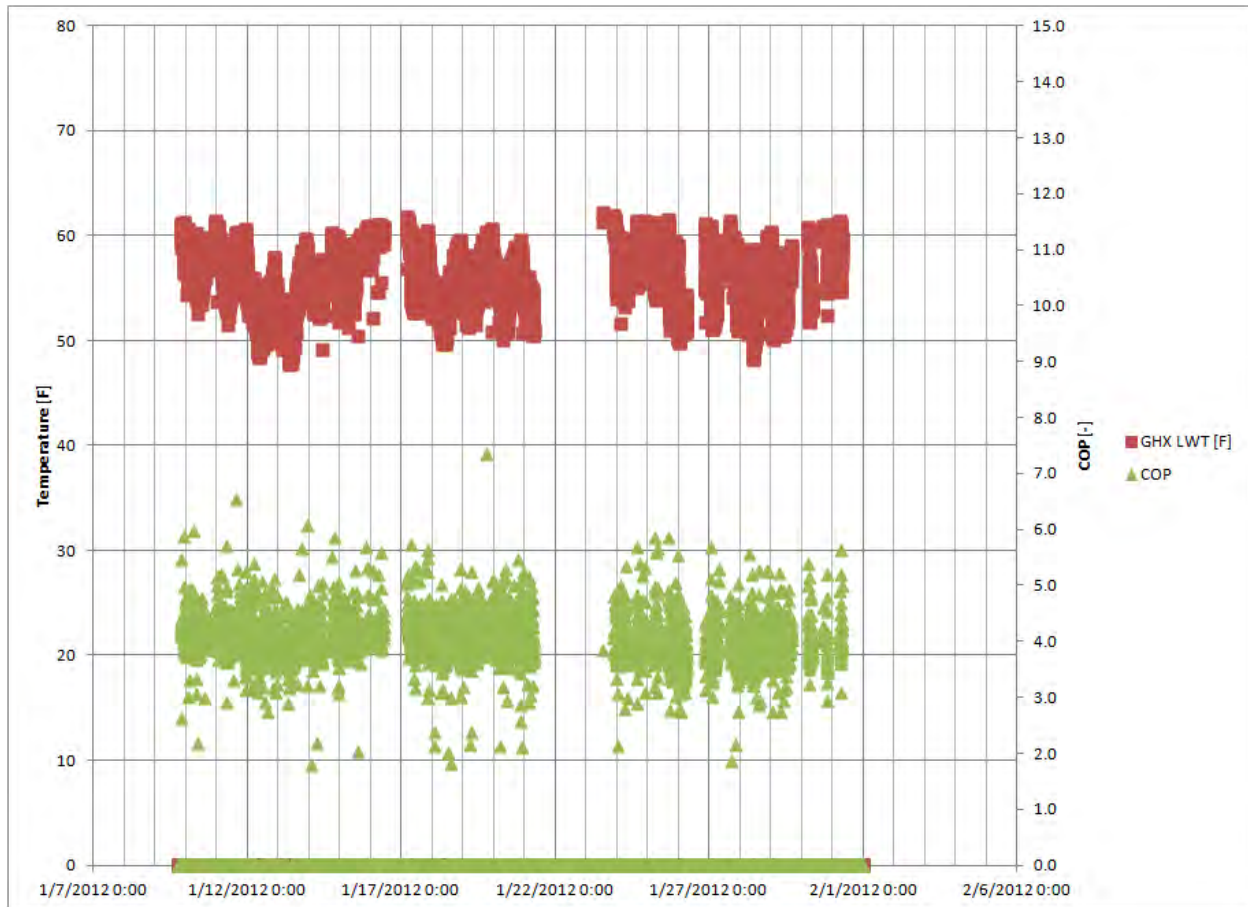


Figure B-2-9-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 10 (8528)

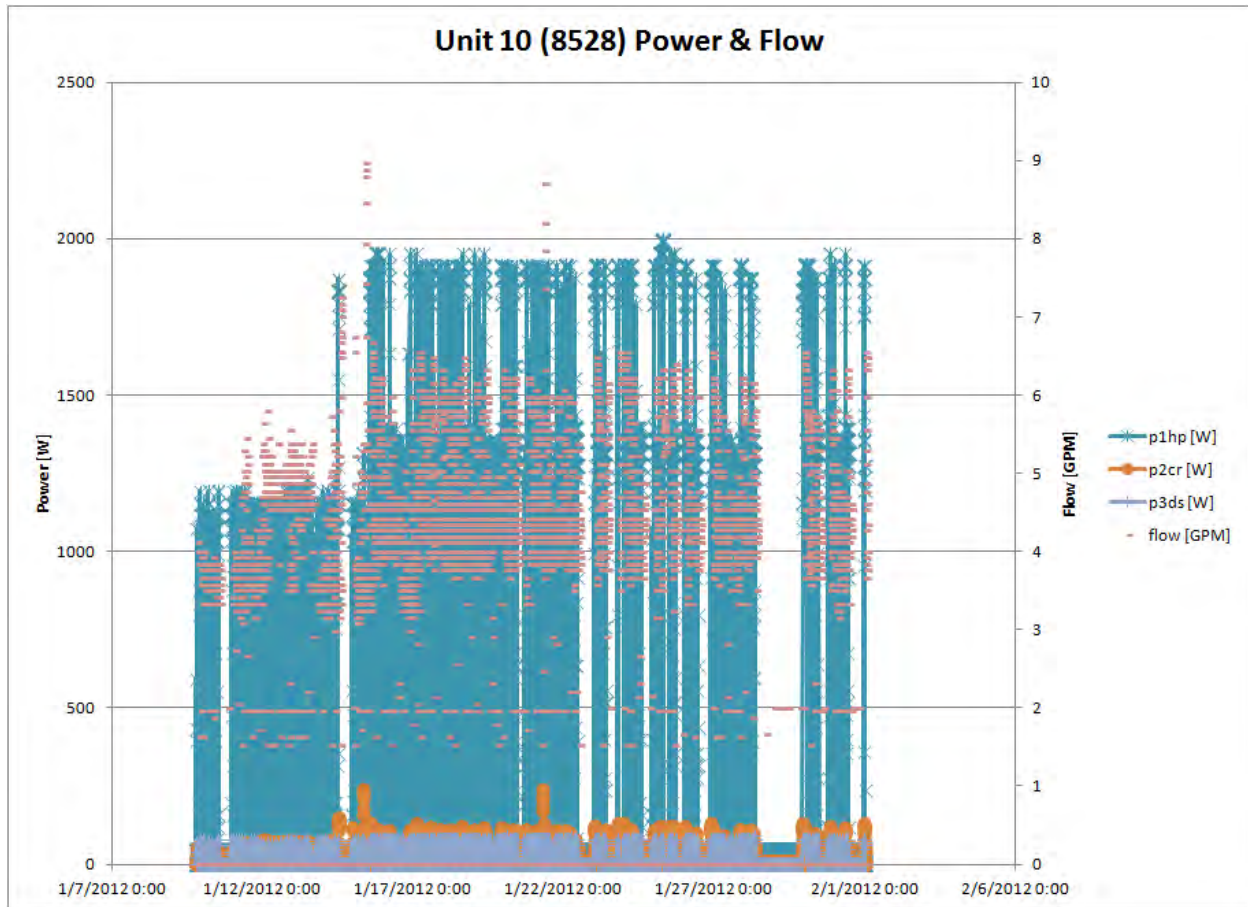


Figure B-2-10-1. Measured power and flow rate

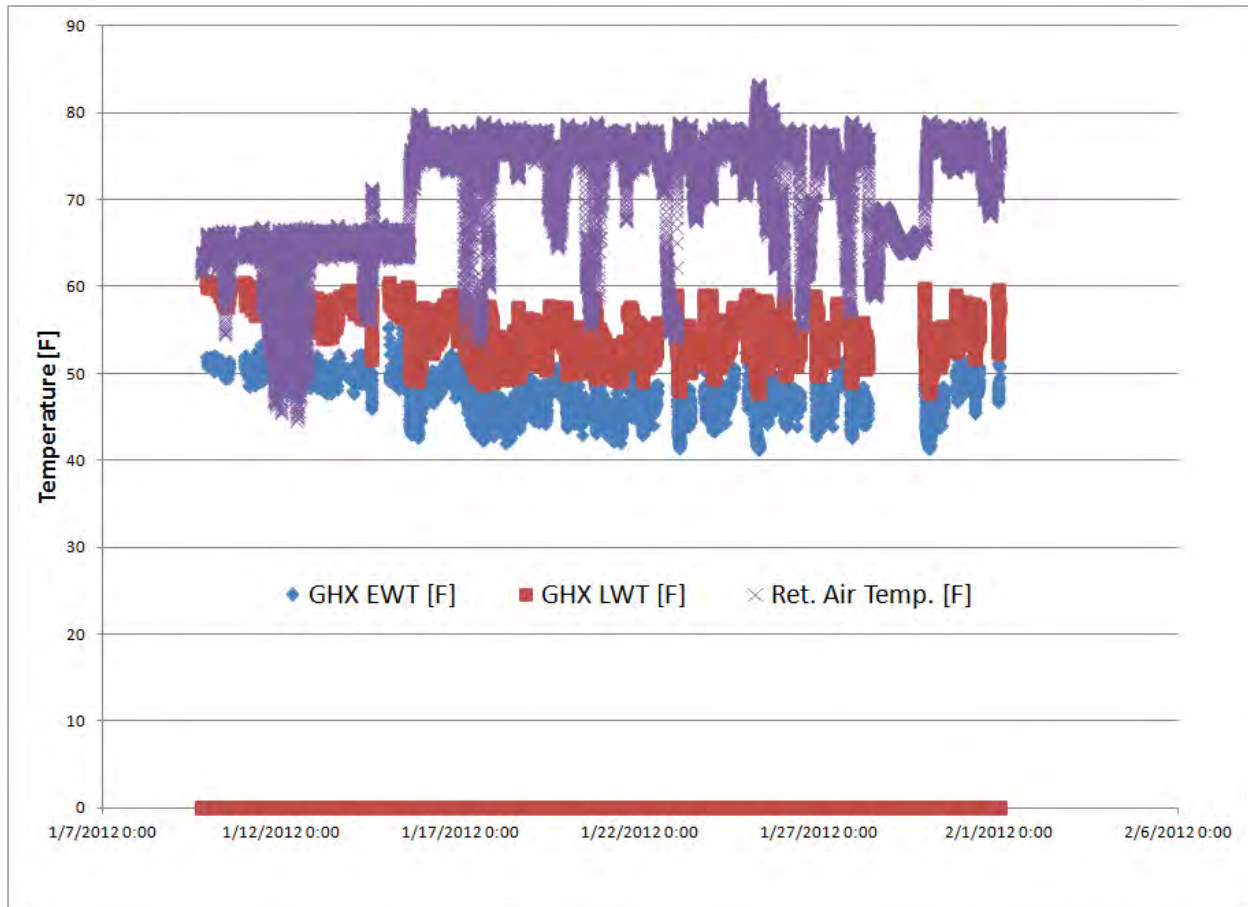


Figure B-2-10-2. Measured room and loop temperatures

The above chart showed that the thermostat set-point was about 66.5°F before 1/15/2012 and then it was increased to about 78°F. The heat pump ran at full-load mode frequently after the change of the thermostat set-point. The above two charts indicated that the GSHP system was turned off from 1/28/2012 around 11 am until 1/28/2012 at about 10 pm.

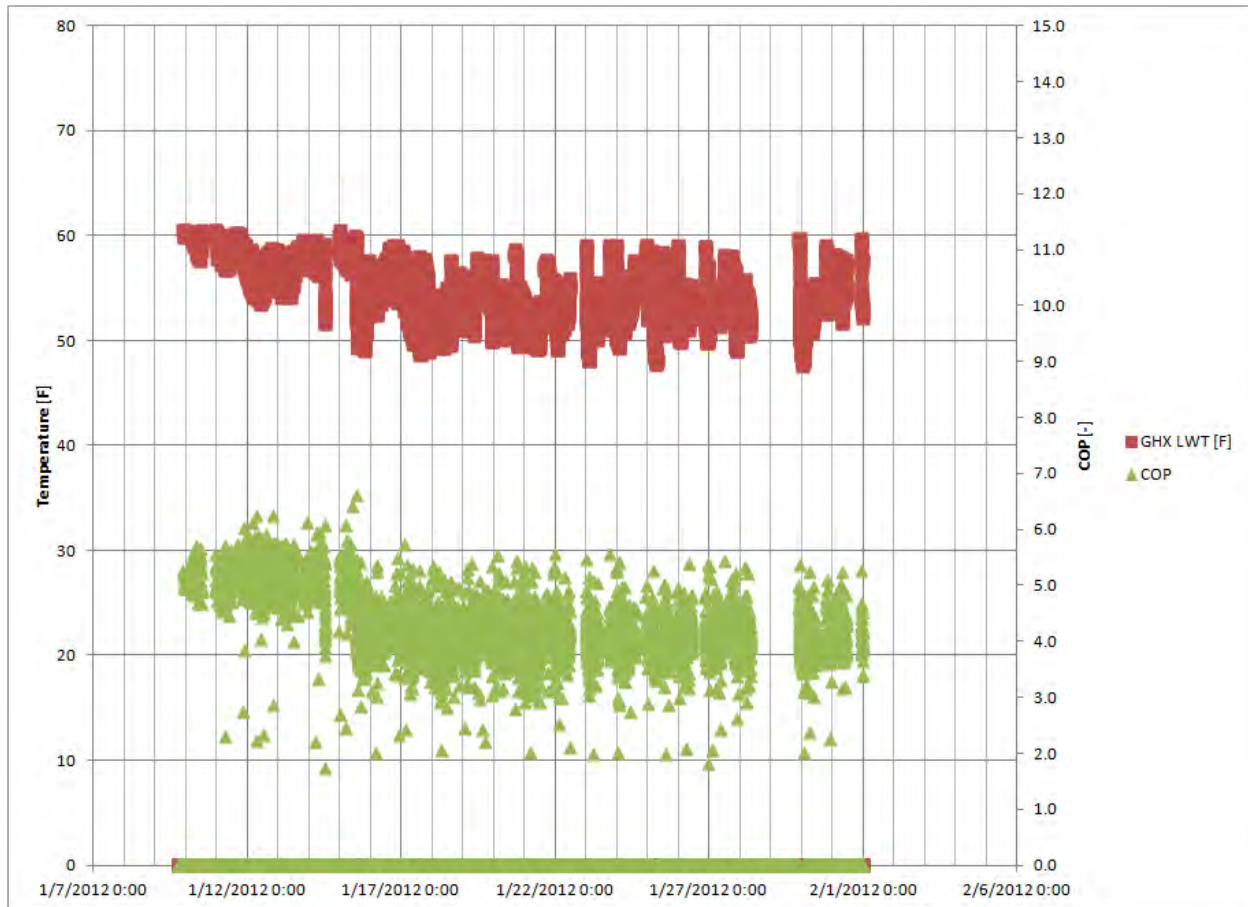


Figure B-2-10-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

With 66.5°F thermostat set point, the GHP system ran at part-load mode and the GHX LFT was above 53.5°F. The COP during this period was between 4.3 and 5.9 for most time. However, when the set point was increased to 78°F, the heat pump ran at the full-load mode frequently and the COP was reduced to the range from 5.2 to 3.2 for most time.

B-3: FEBRUARY 2012

Unit 01 (925)

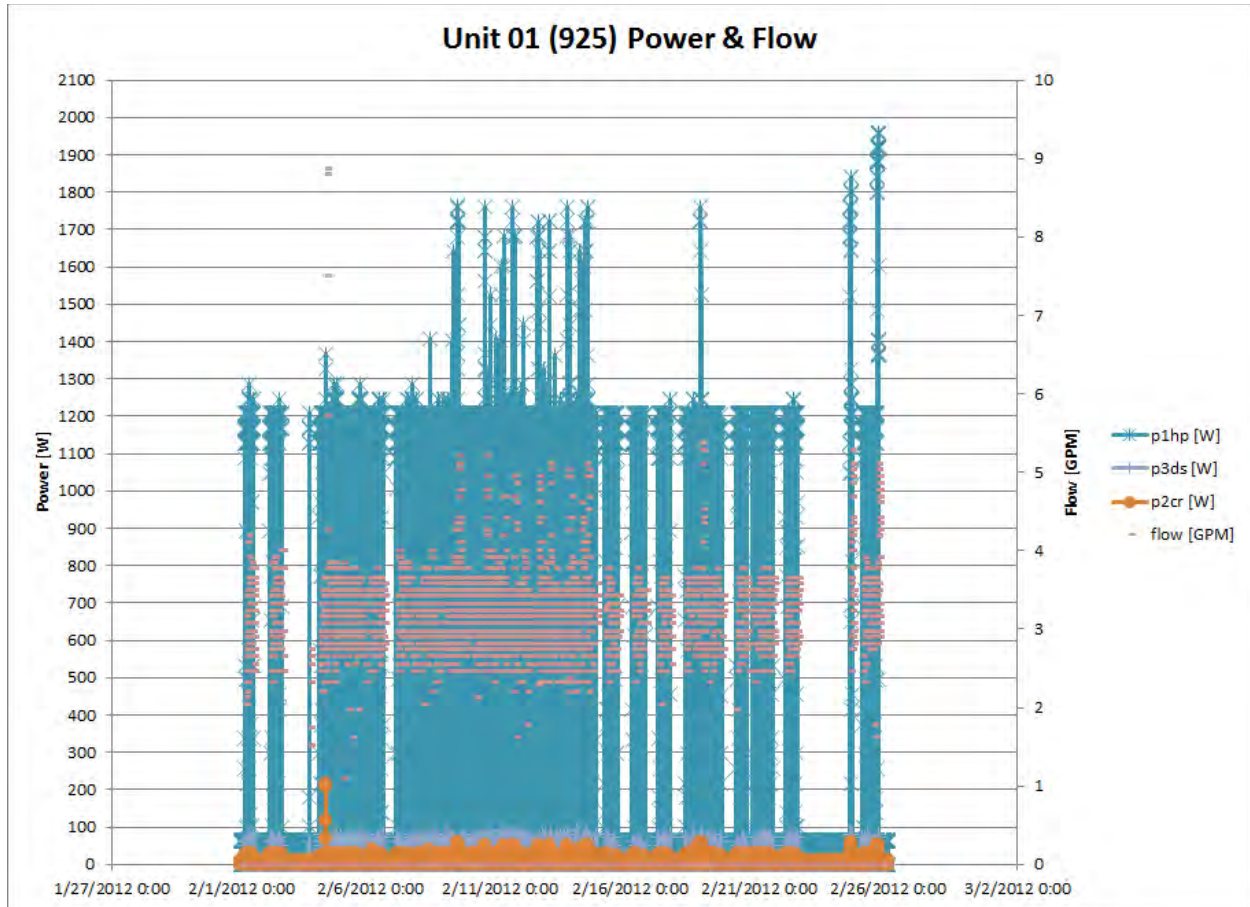


Figure B-3-1-1. Measured power and flow rate

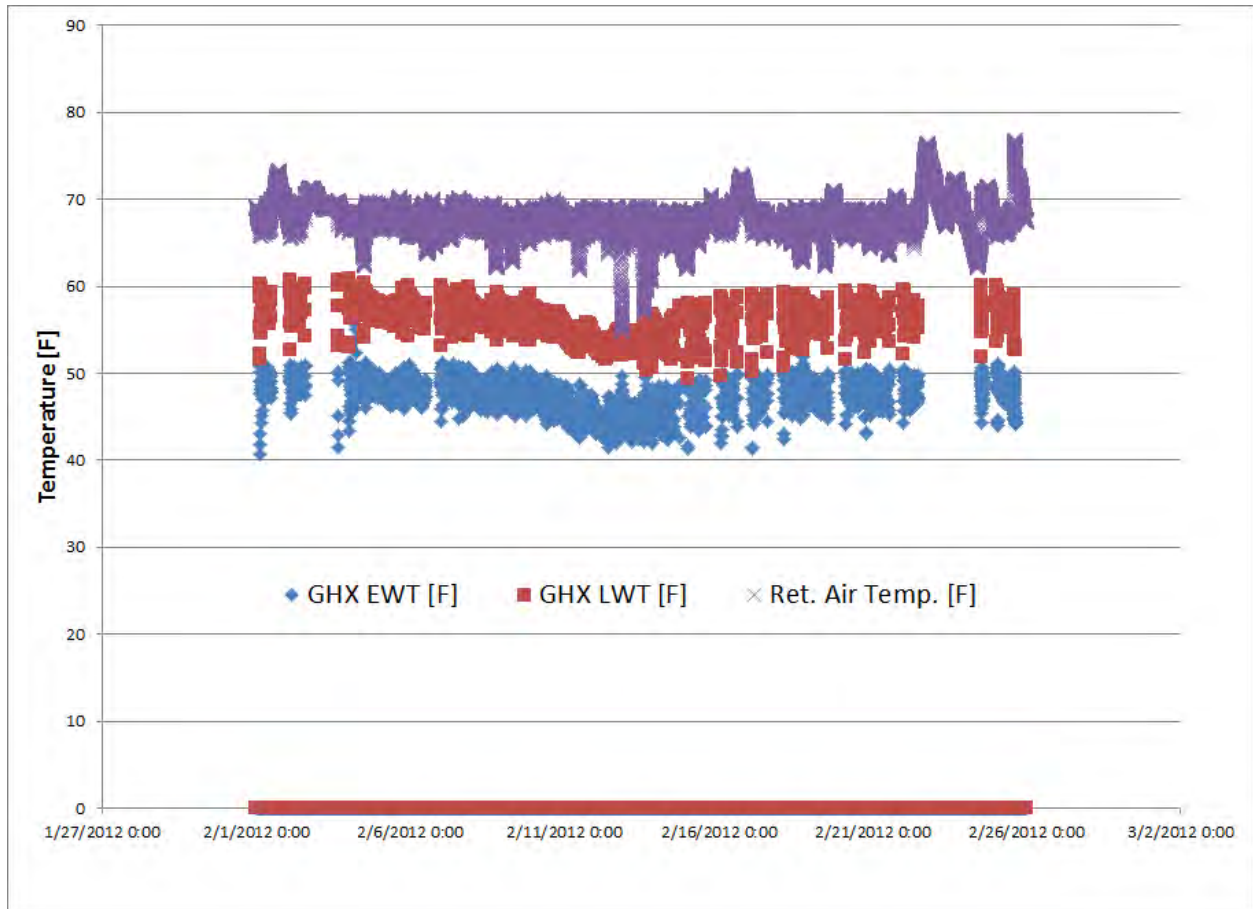


Figure B-3-1-2. Measured room and loop temperatures

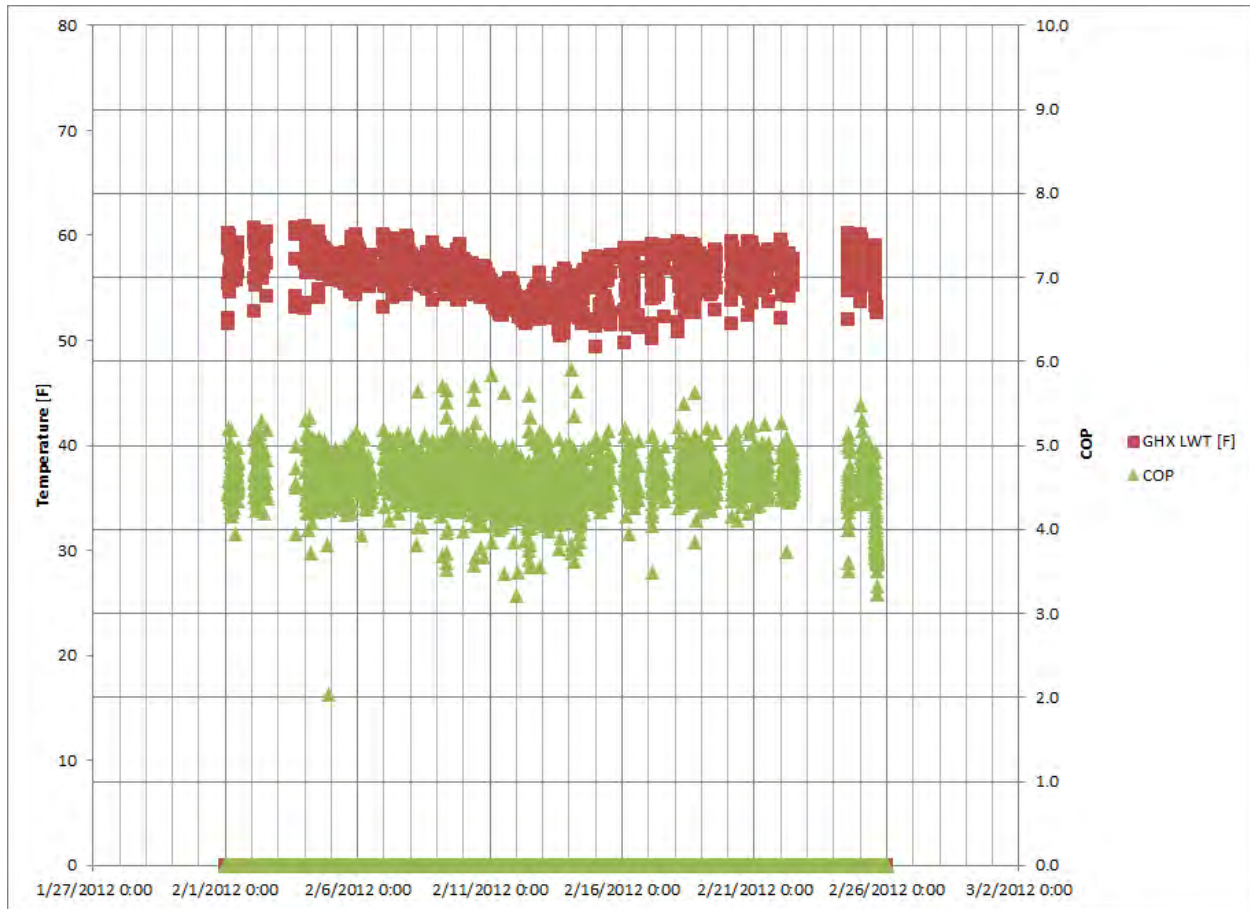


Figure B-3-1-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 02 (916)

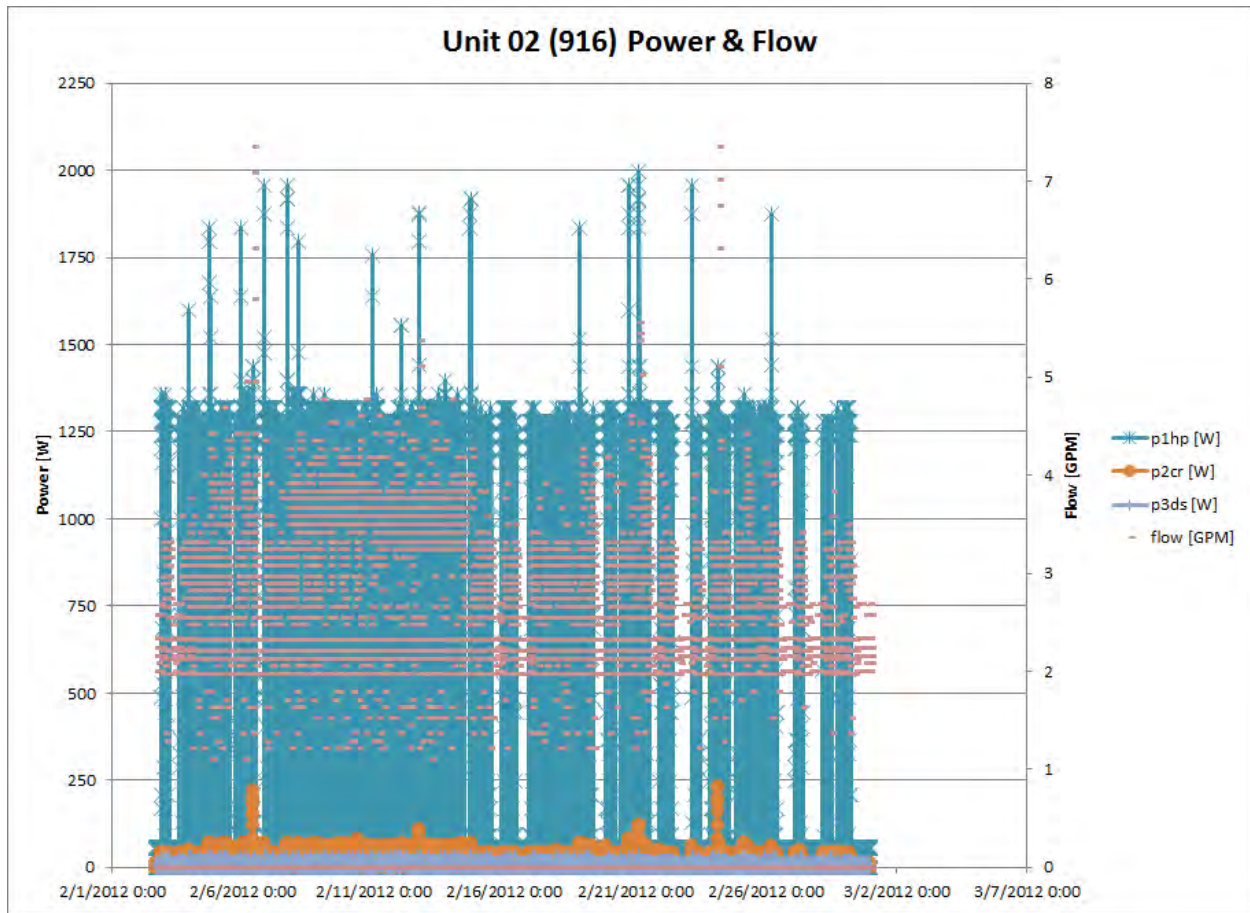


Figure B-3-2-1. Measured power and flow rate

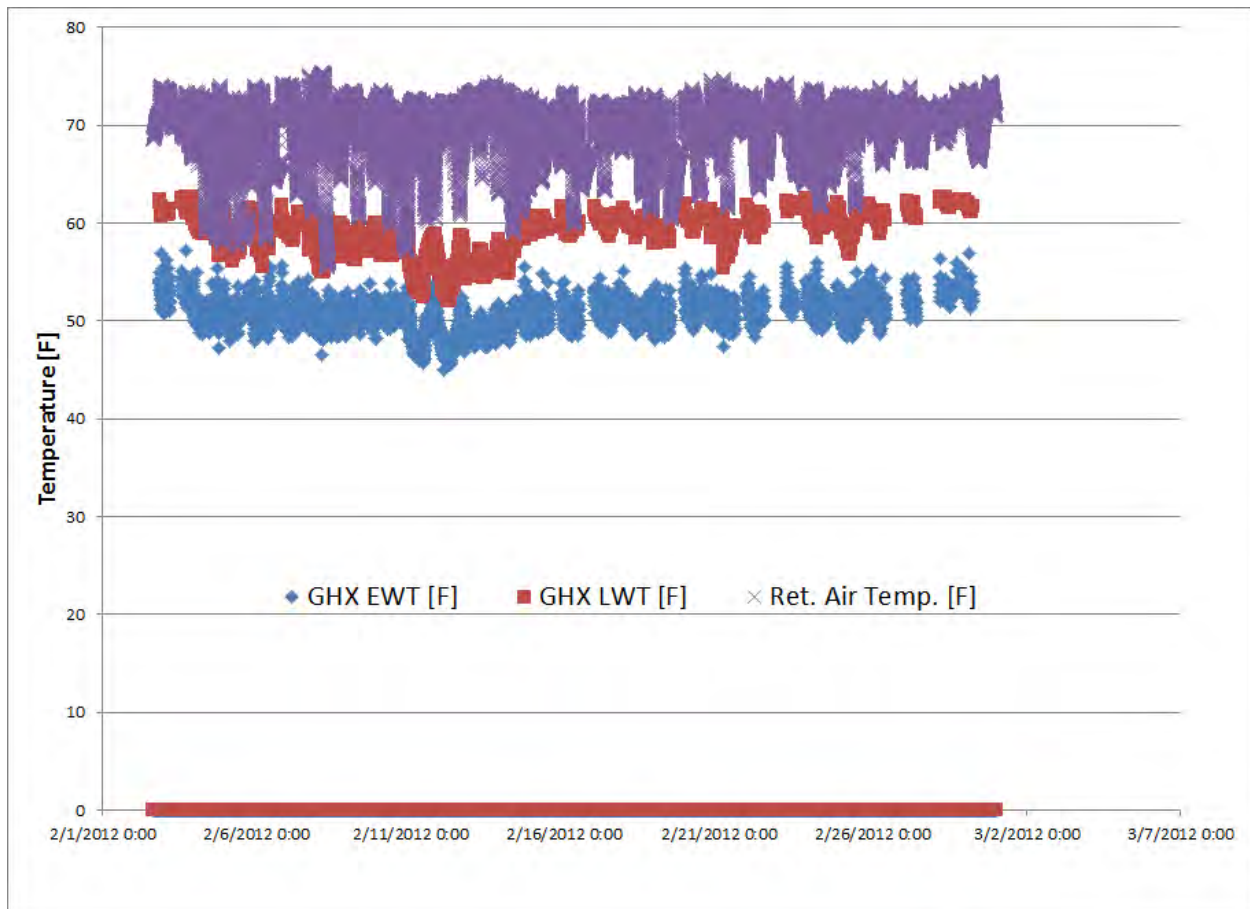


Figure B-3-2-2. Measured room and loop temperatures

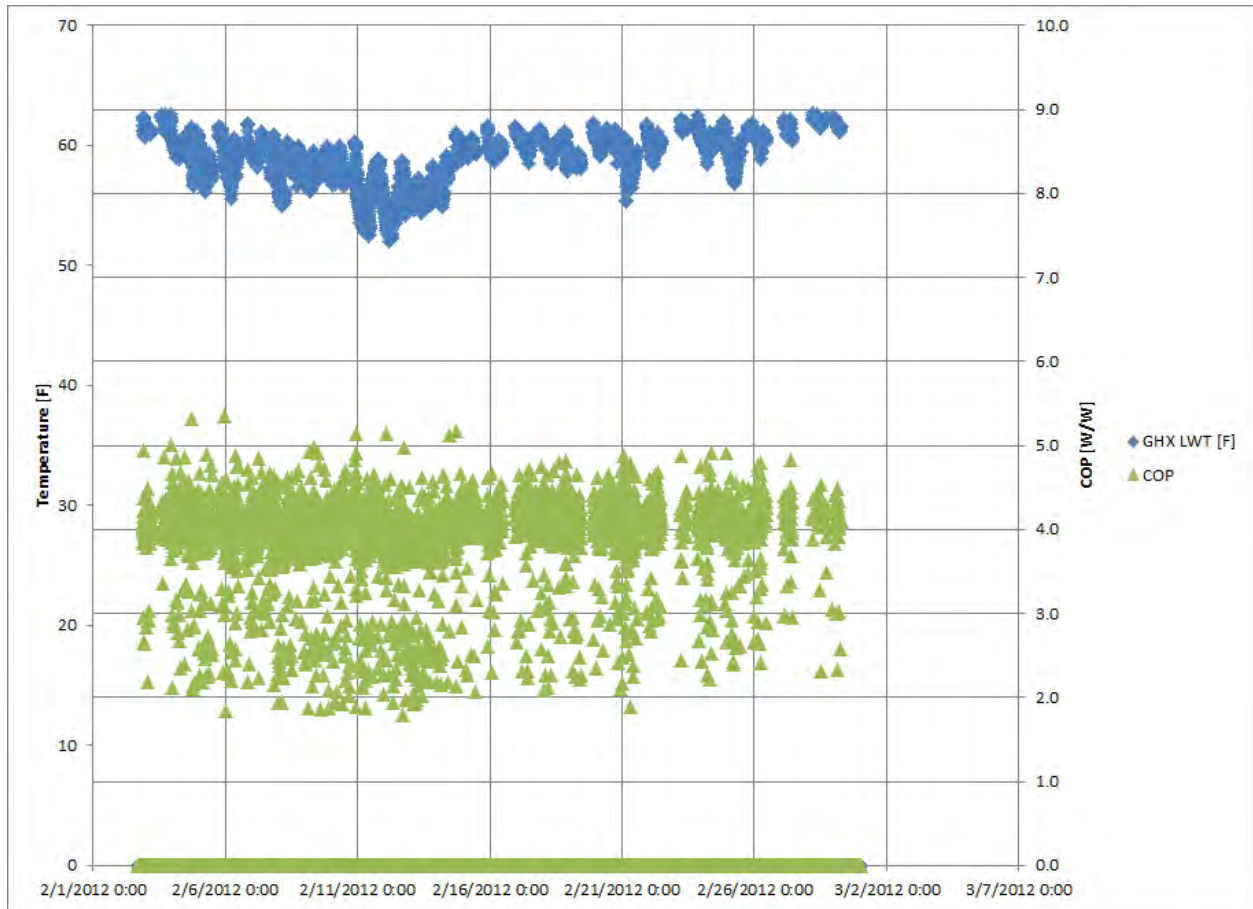


Figure B-3-2-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 03 (833)

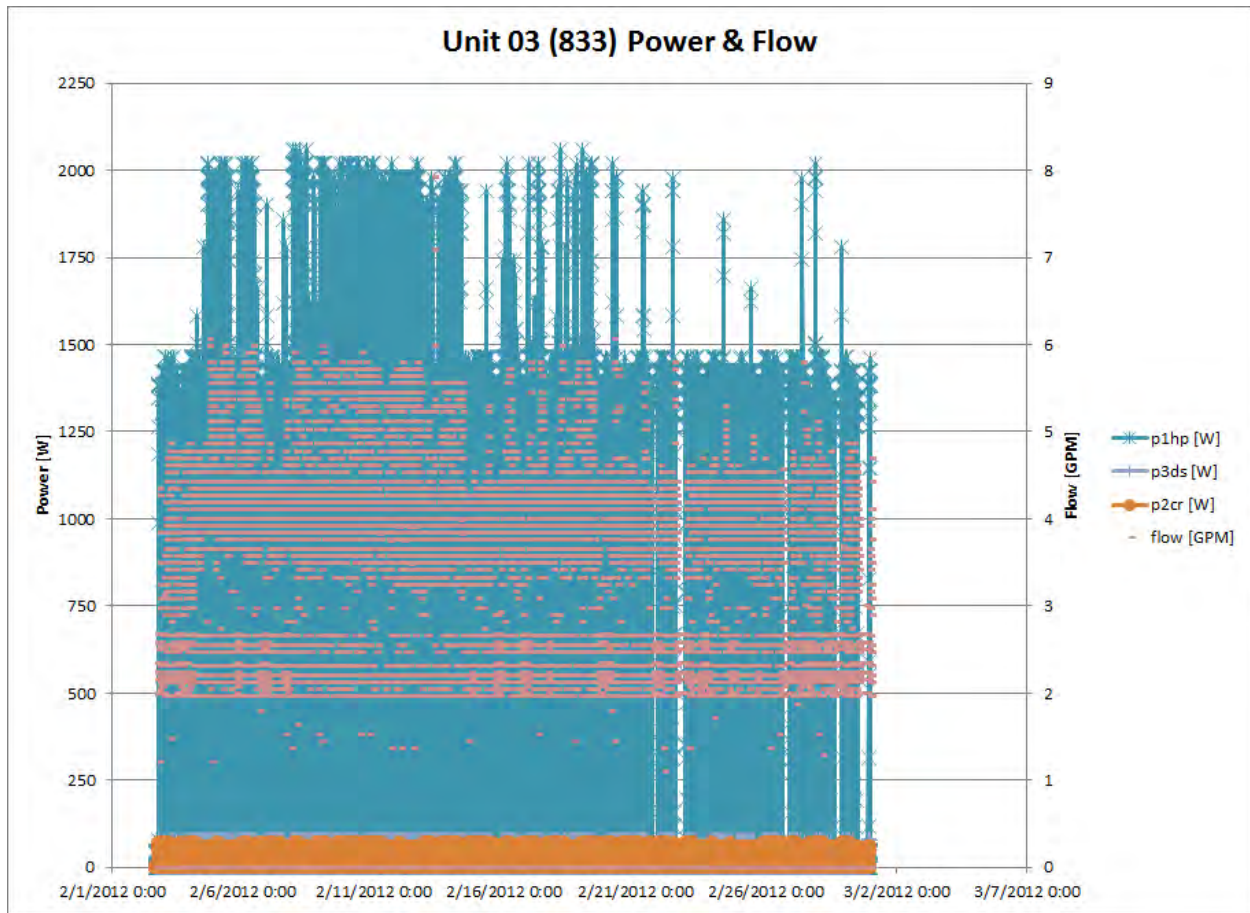


Figure B-3-3-1. Measured power and flow rate

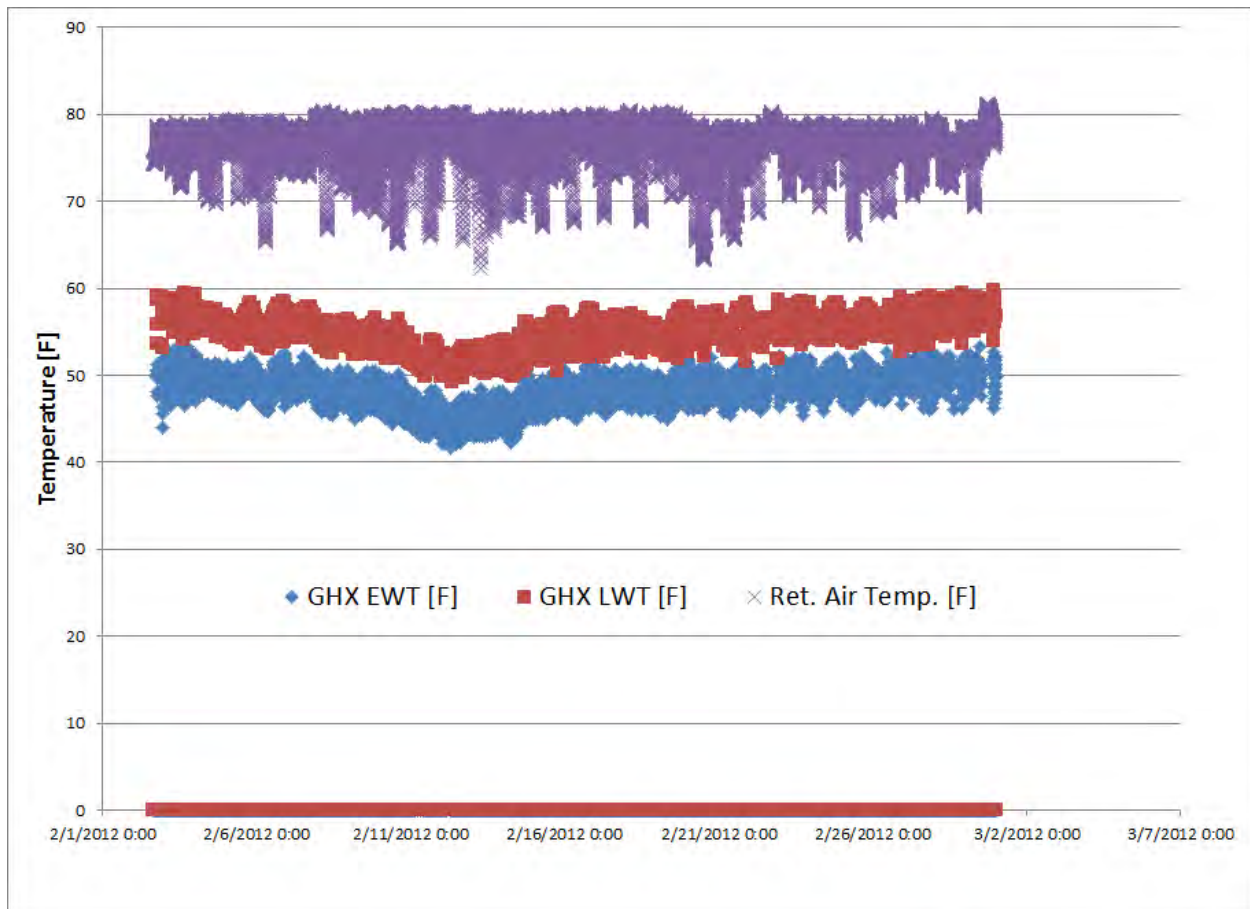


Figure B-3-3-2. Measured room and loop temperatures

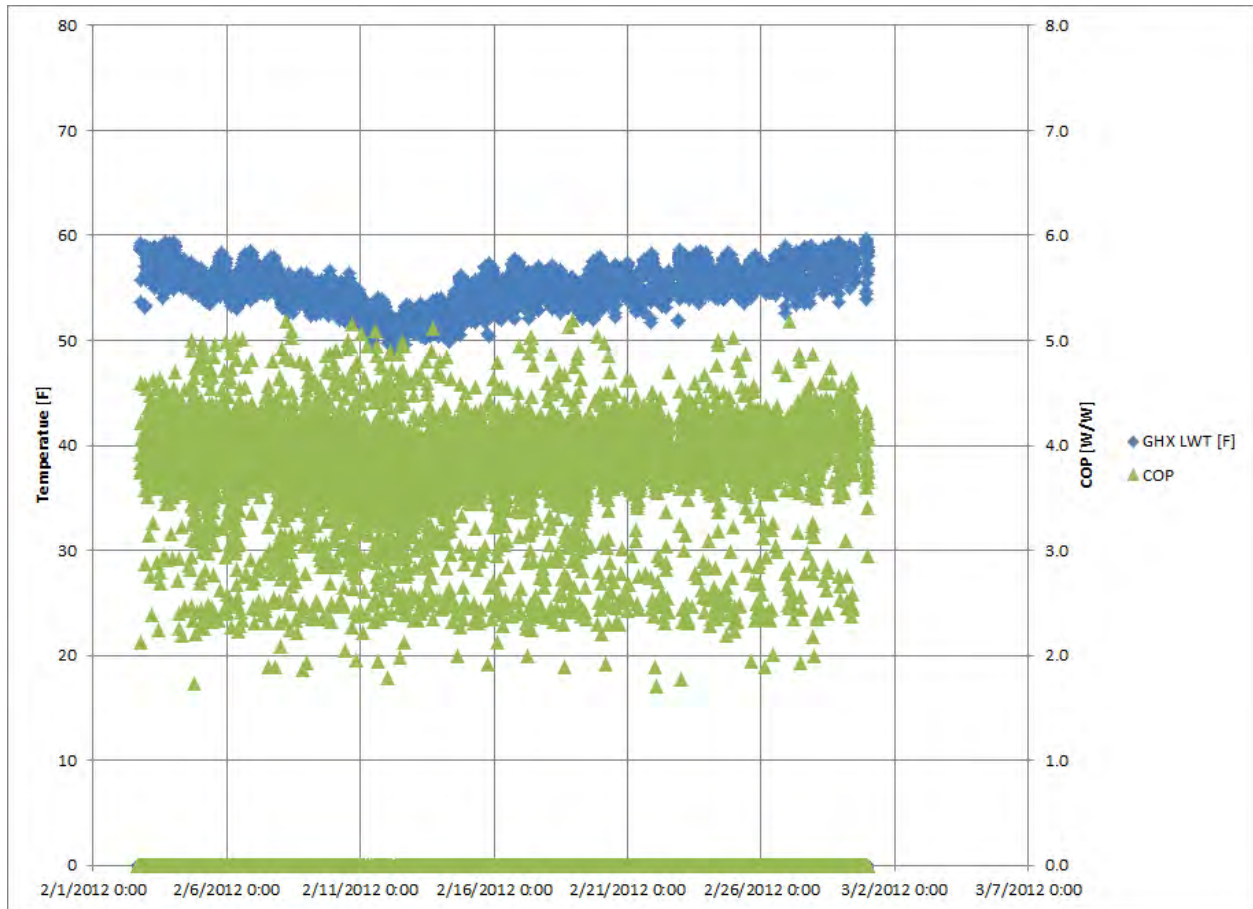


Figure B-3-3-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 04 (932)

No data available during February, 2012 due to a hard drive failure of the DAS system for this home.

Unit 05 (813)

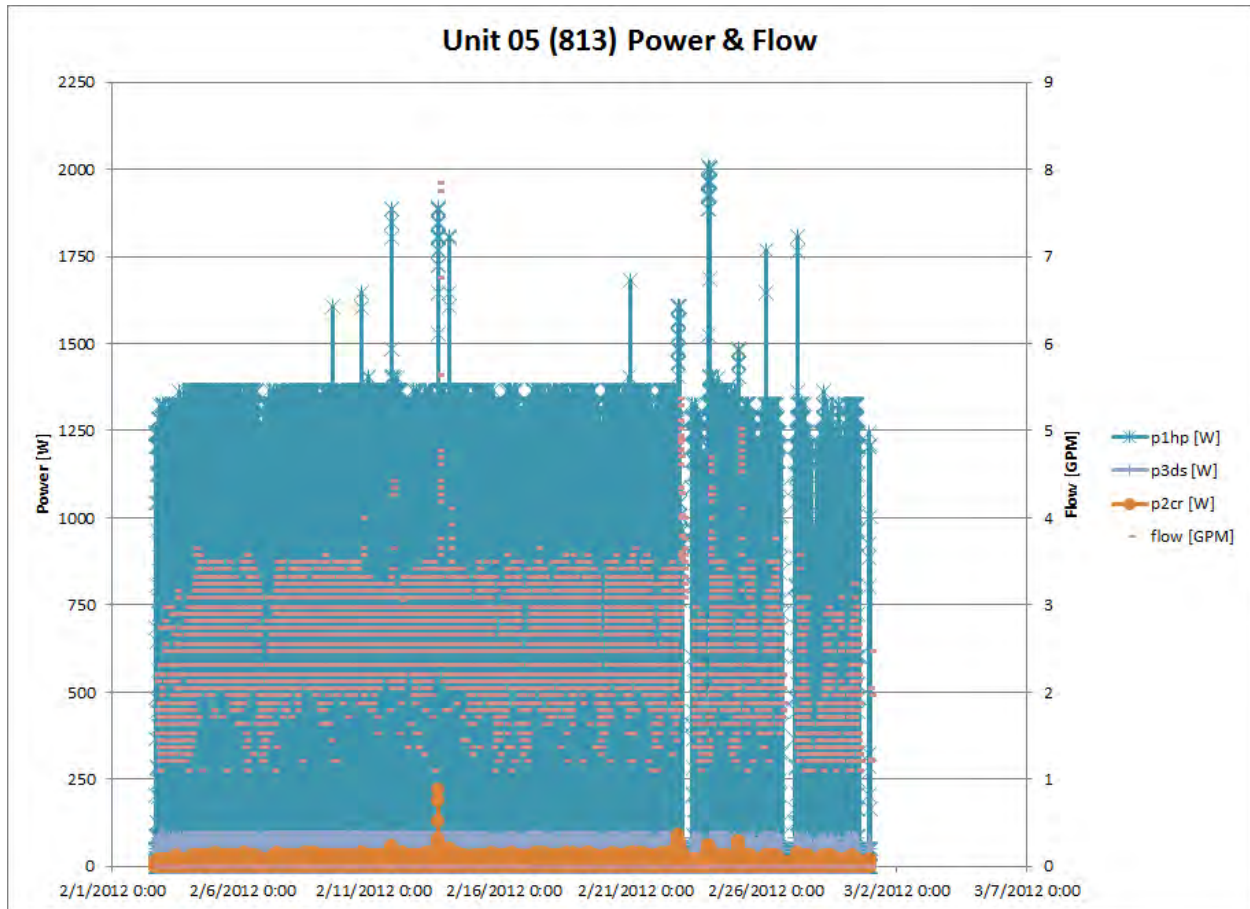


Figure B-3-5-1. Measured power and flow rate

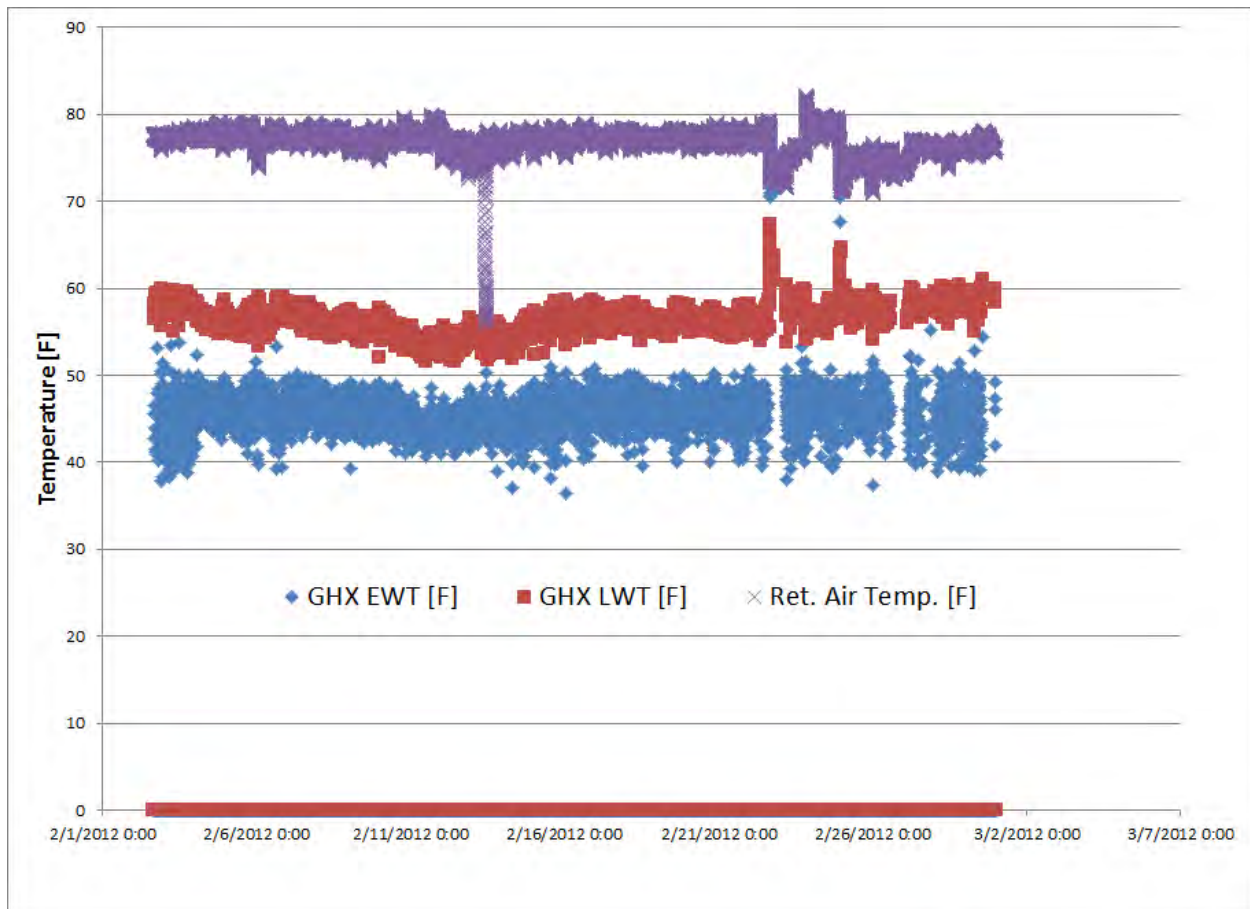


Figure B-3-5-2. Measured room and loop temperatures

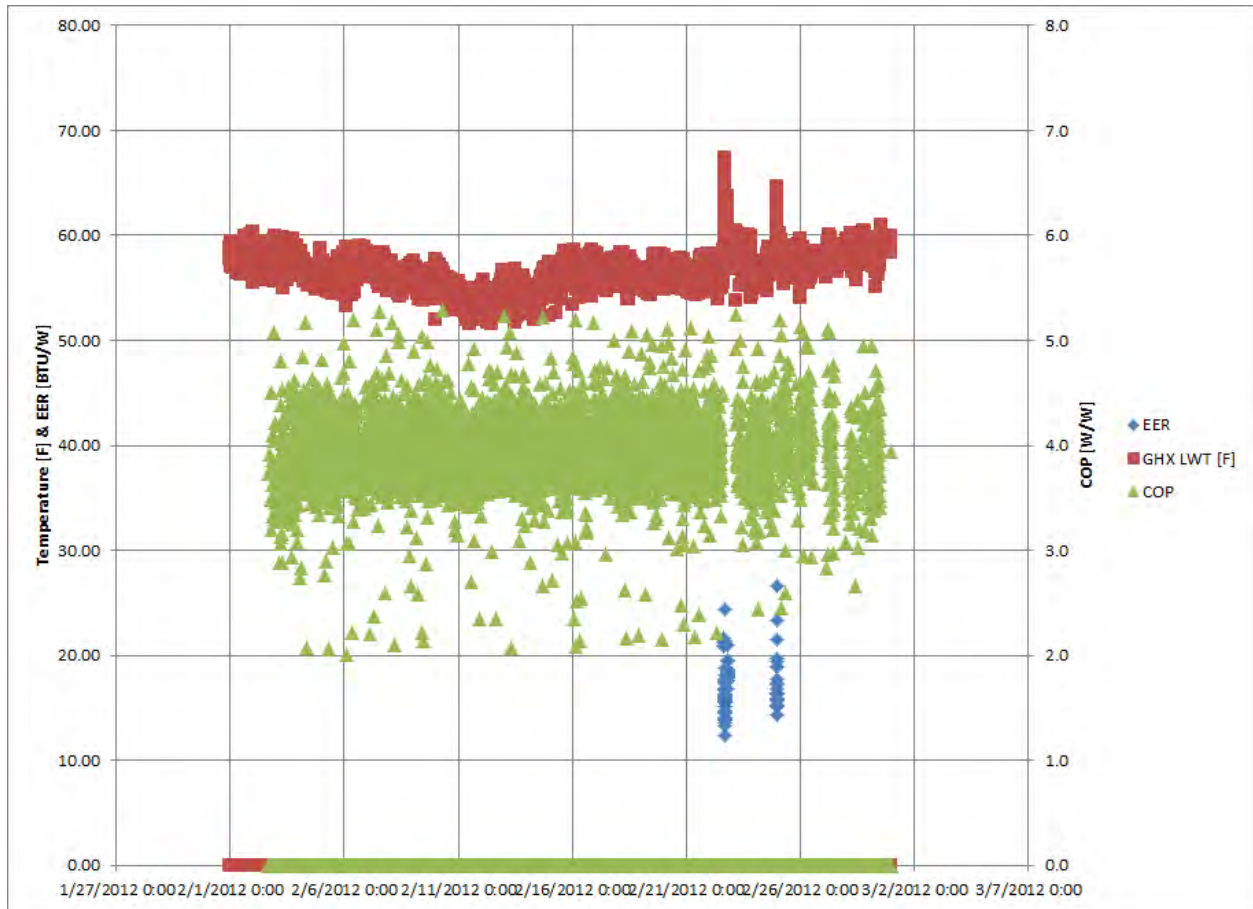


Figure B-3-5-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 06 (824)

No data available during February, 2012 due to a hard drive failure of the DAS system for this home.

Unit 07 (928)

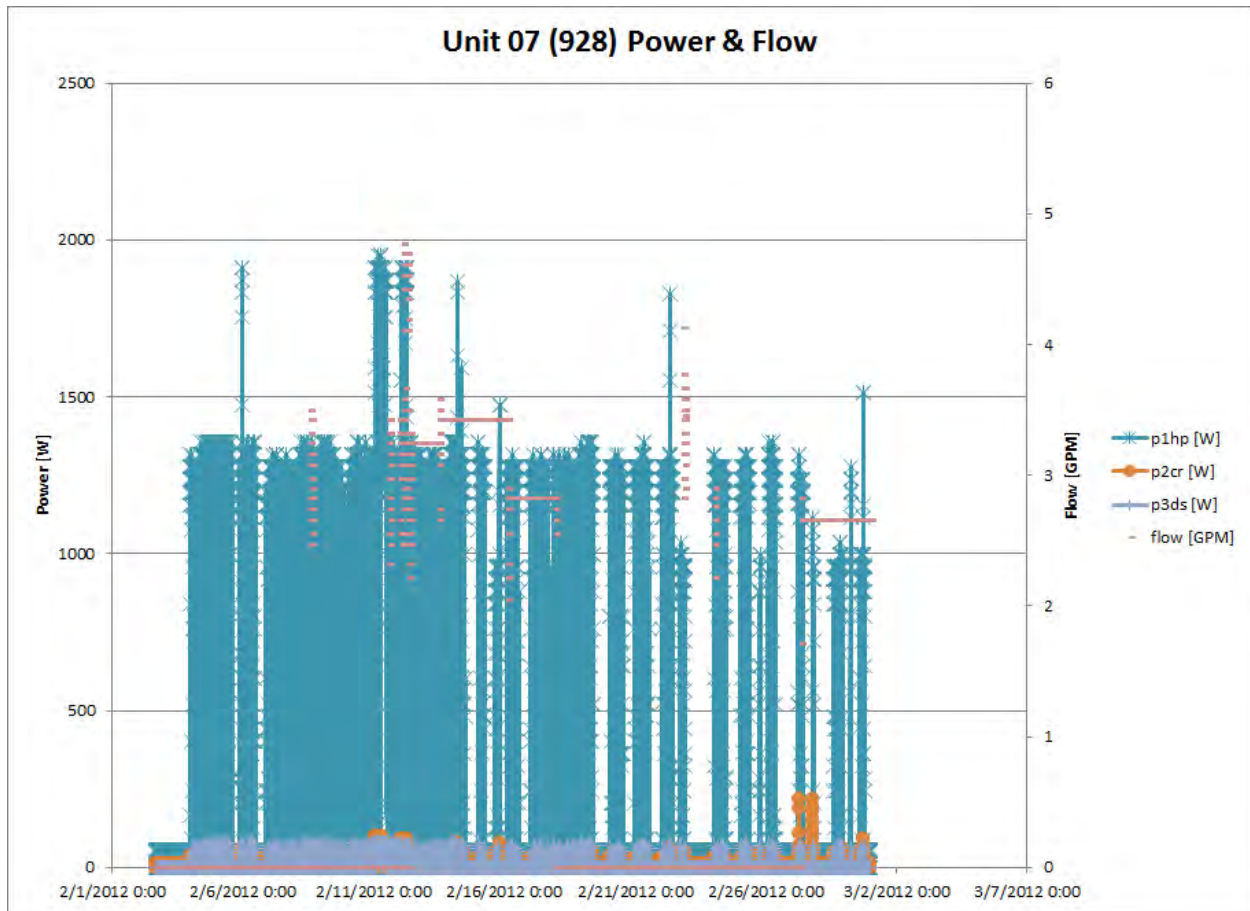


Figure B-3-7-1. Measured power and flow rate

The above chart indicates that flow data was missing during most time of February, 2012.

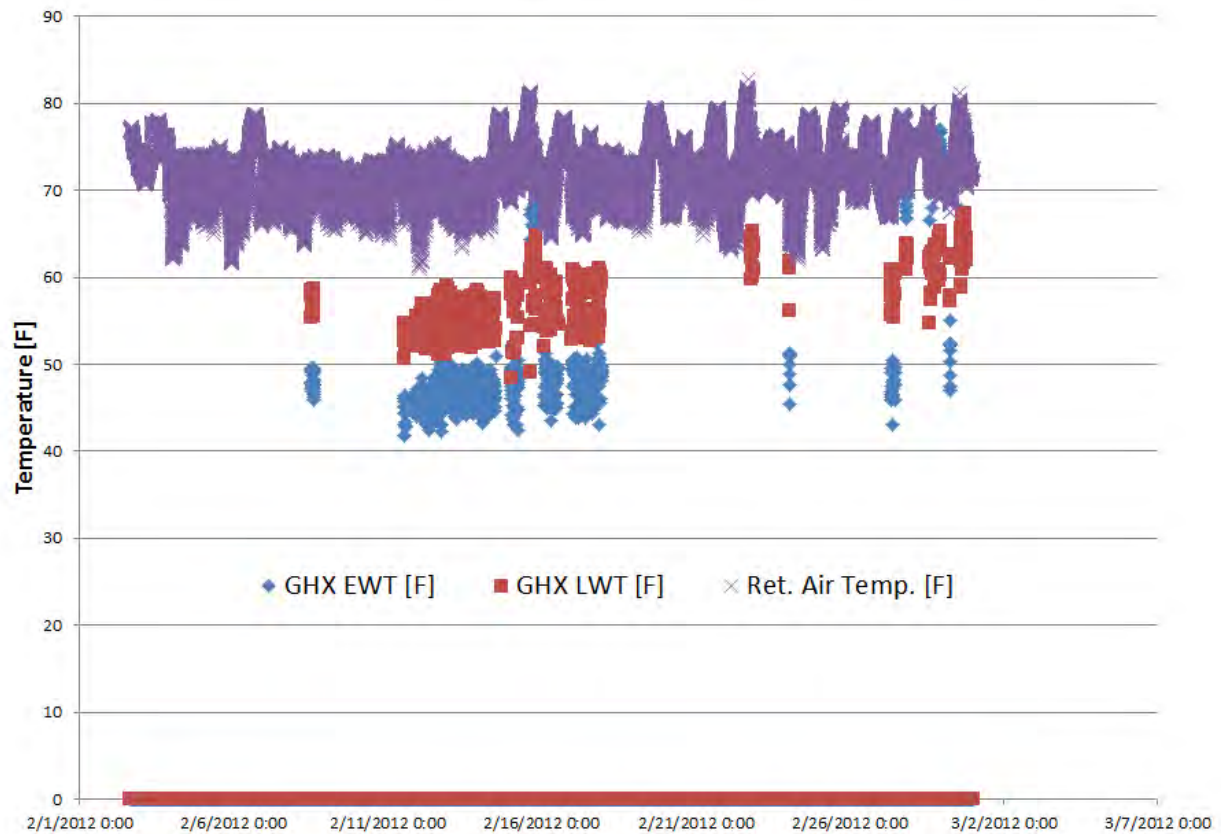


Figure B-3-7-2. Measured room and loop temperatures

There is no chart for COP and EER for February, 2012 since many flow rate data were missing.

Unit 08 (829)

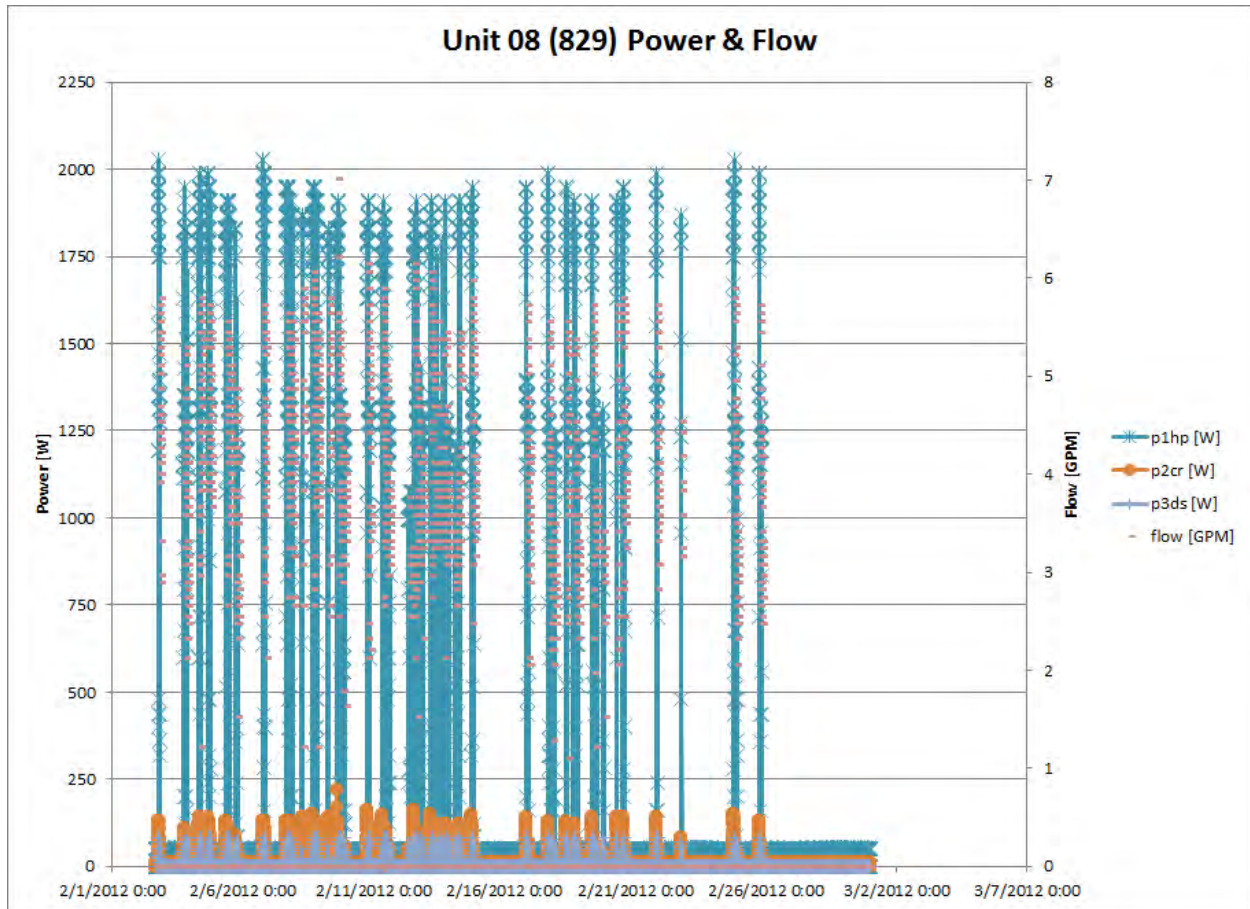


Figure B-3-8-1. Measured power and flow rate

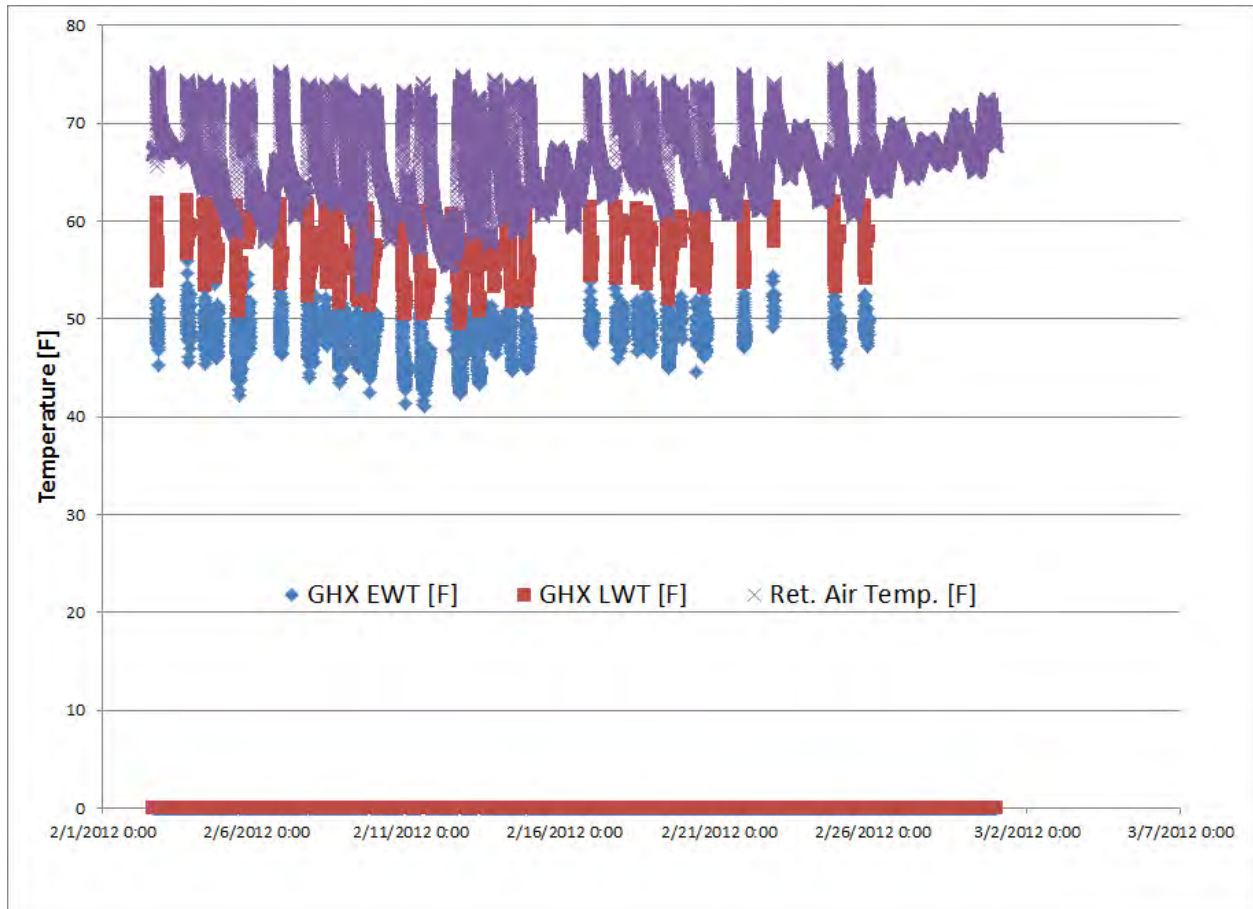


Figure B-3-8-2. Measured room and loop temperatures

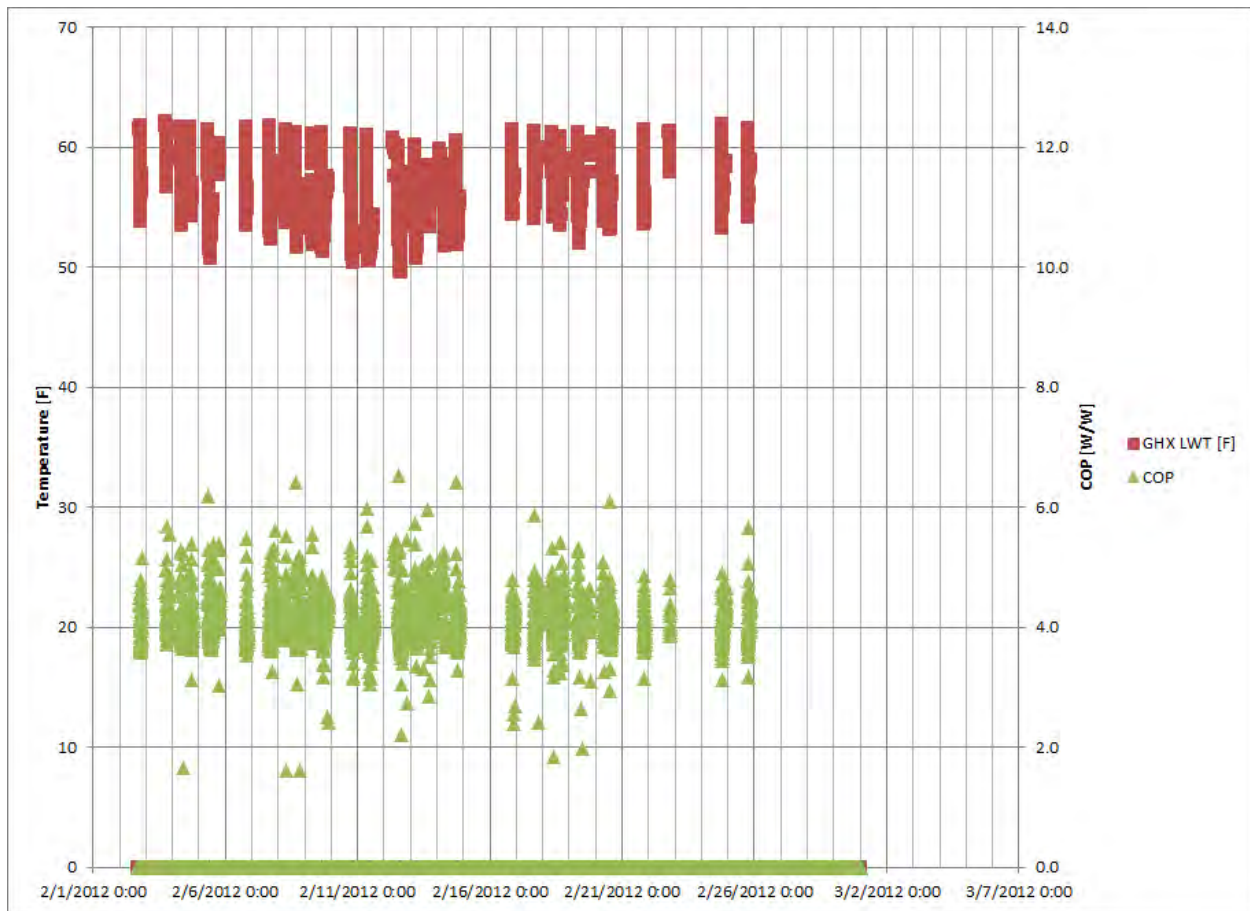


Figure B-3-8-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 09 (944)

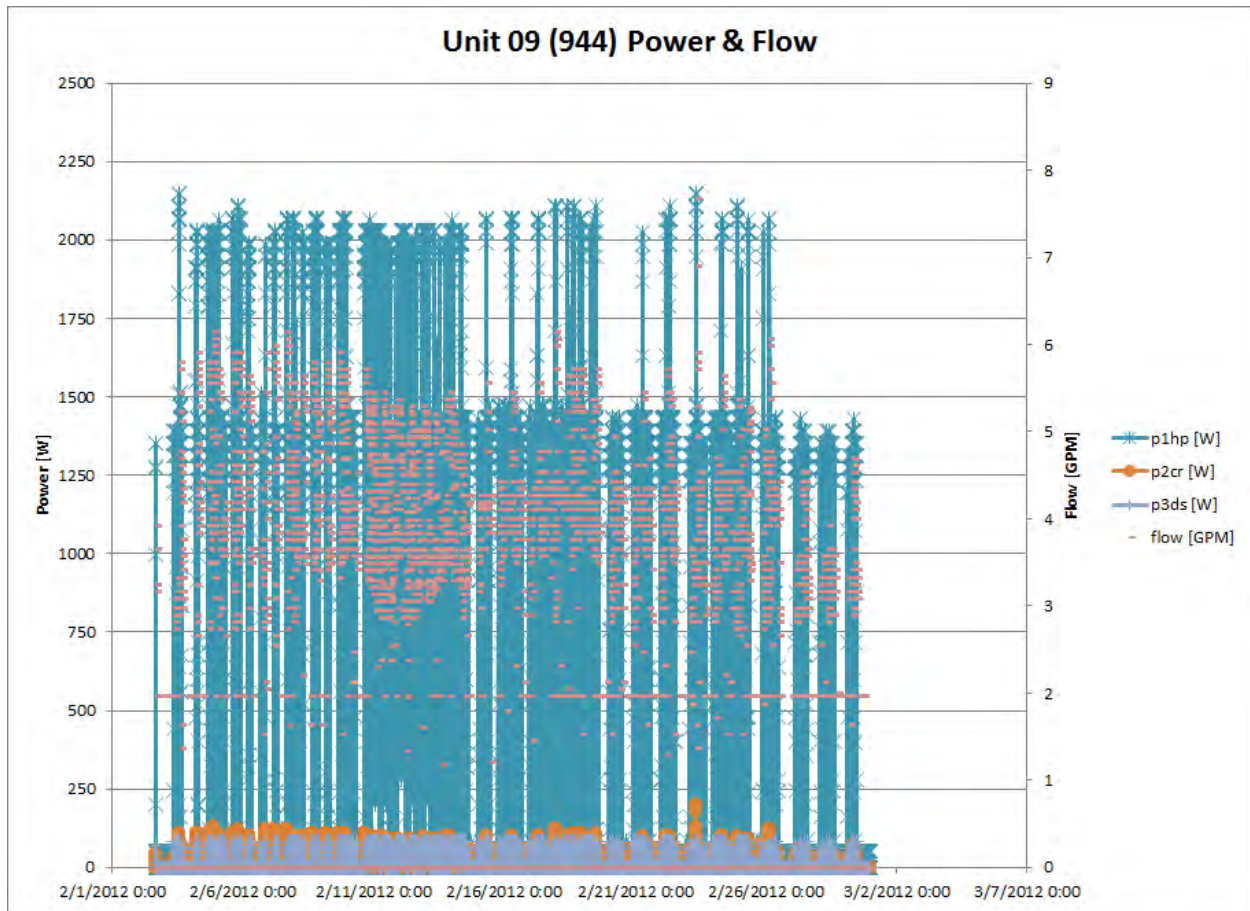


Figure B-3-9-1. Measured power and flow rate

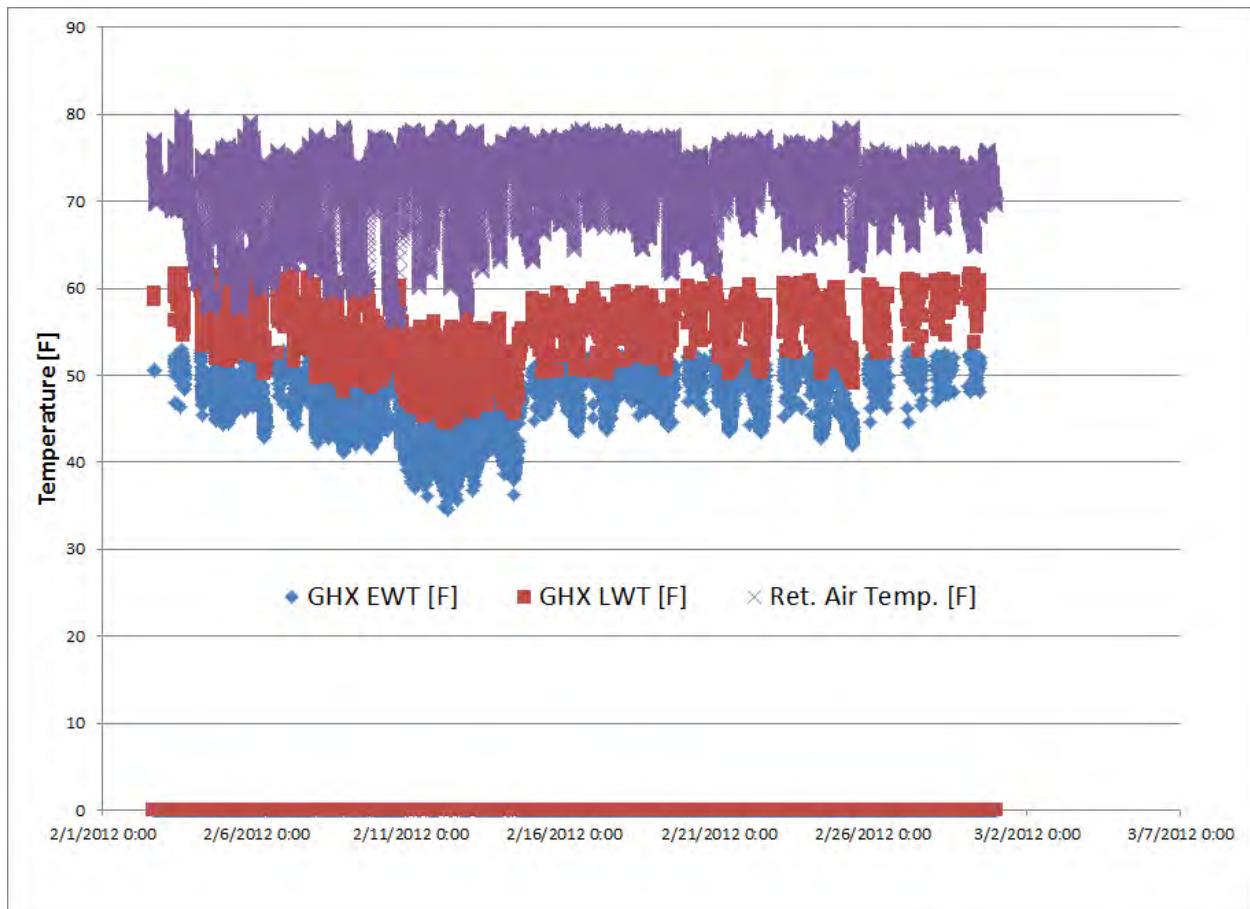


Figure B-3-9-2. Measured room and loop temperatures

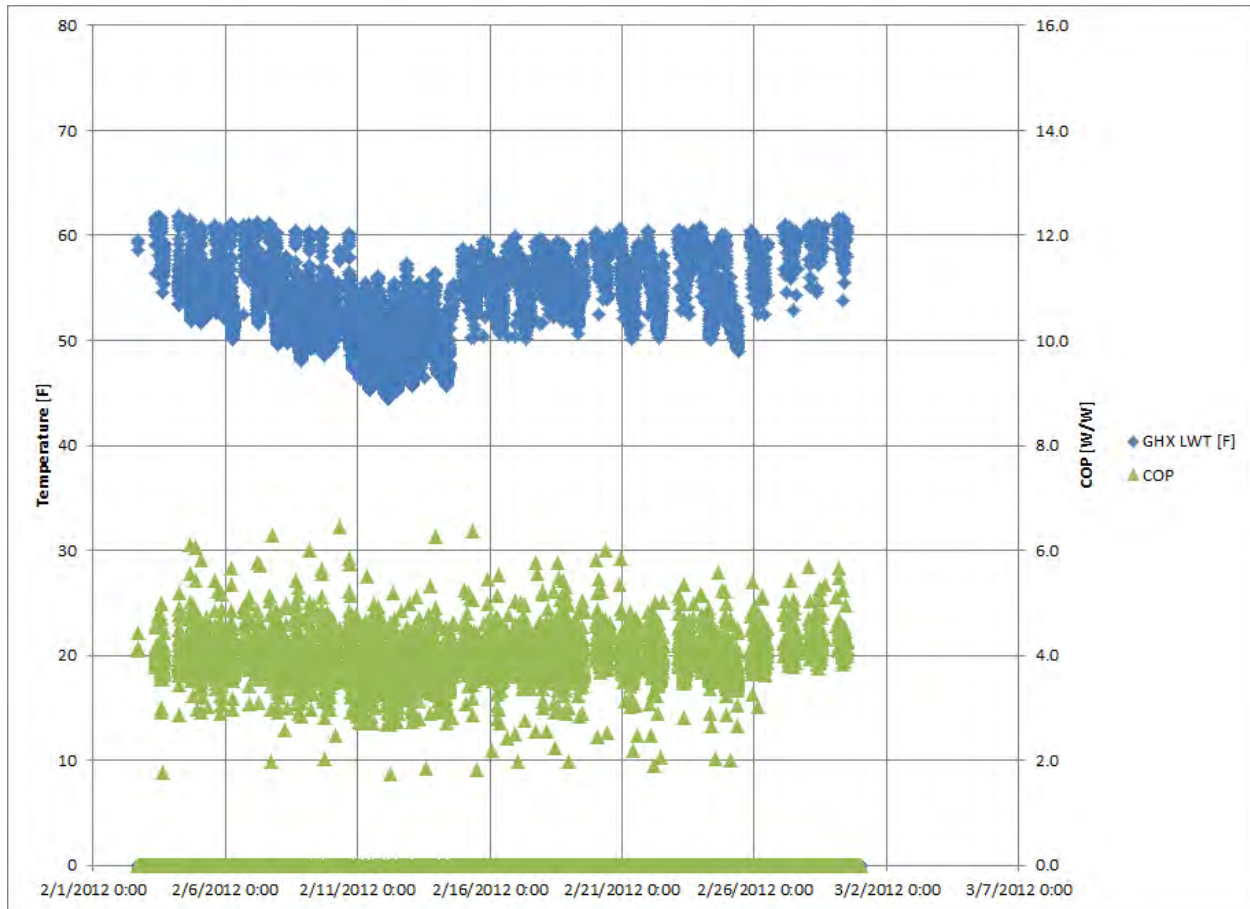


Figure B-3-9-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 10 (8528)

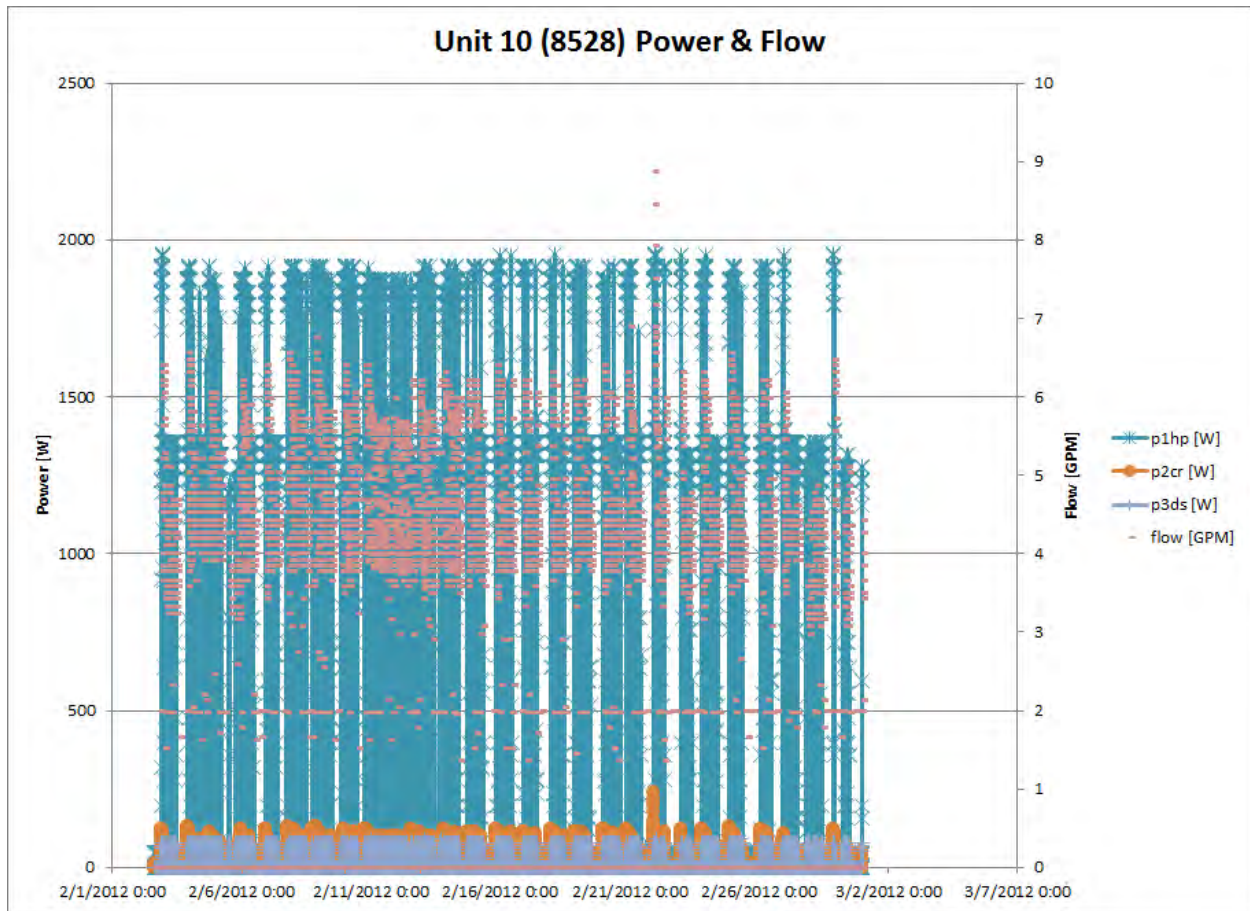


Figure B-3-10-1. Measured power and flow rate

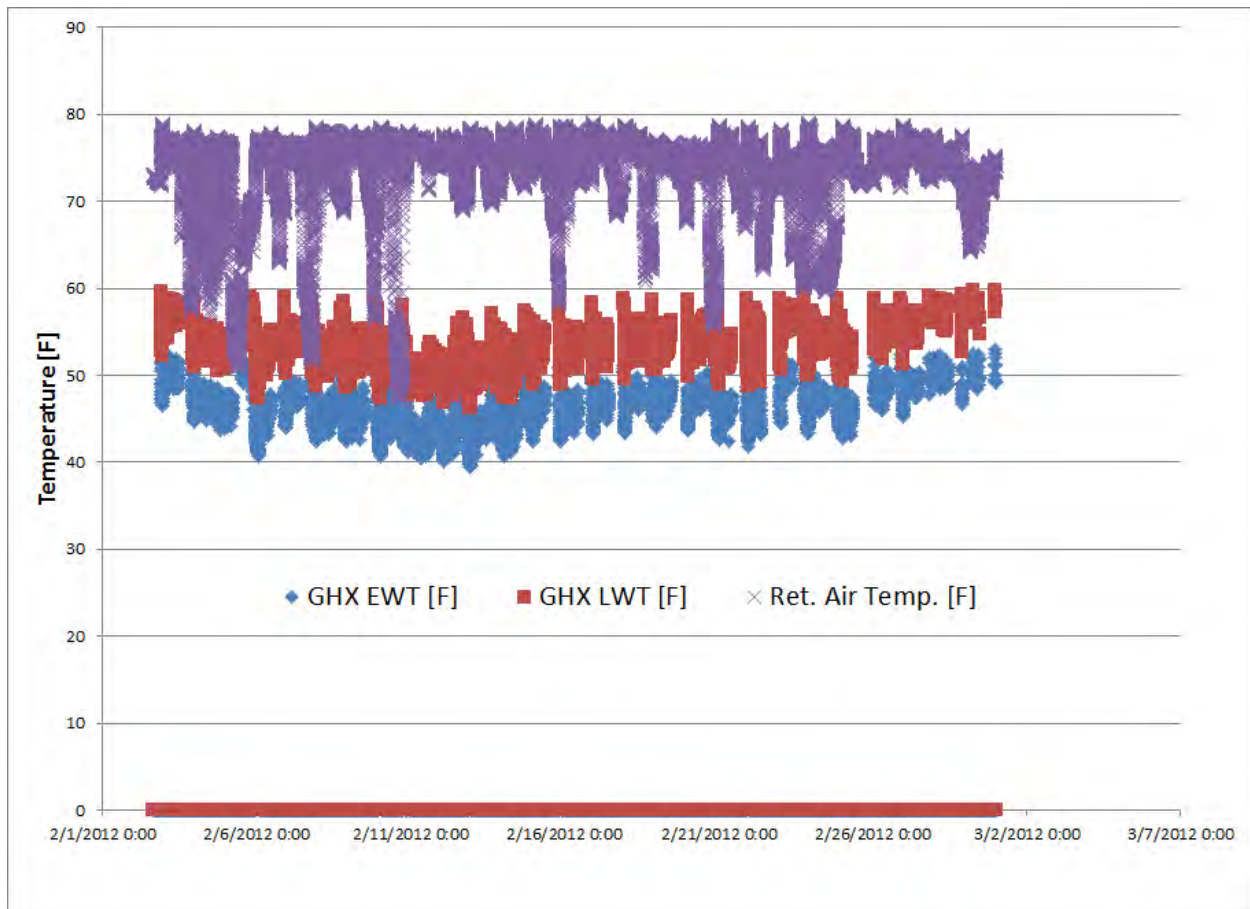


Figure B-3-10-2. Measured room and loop temperatures

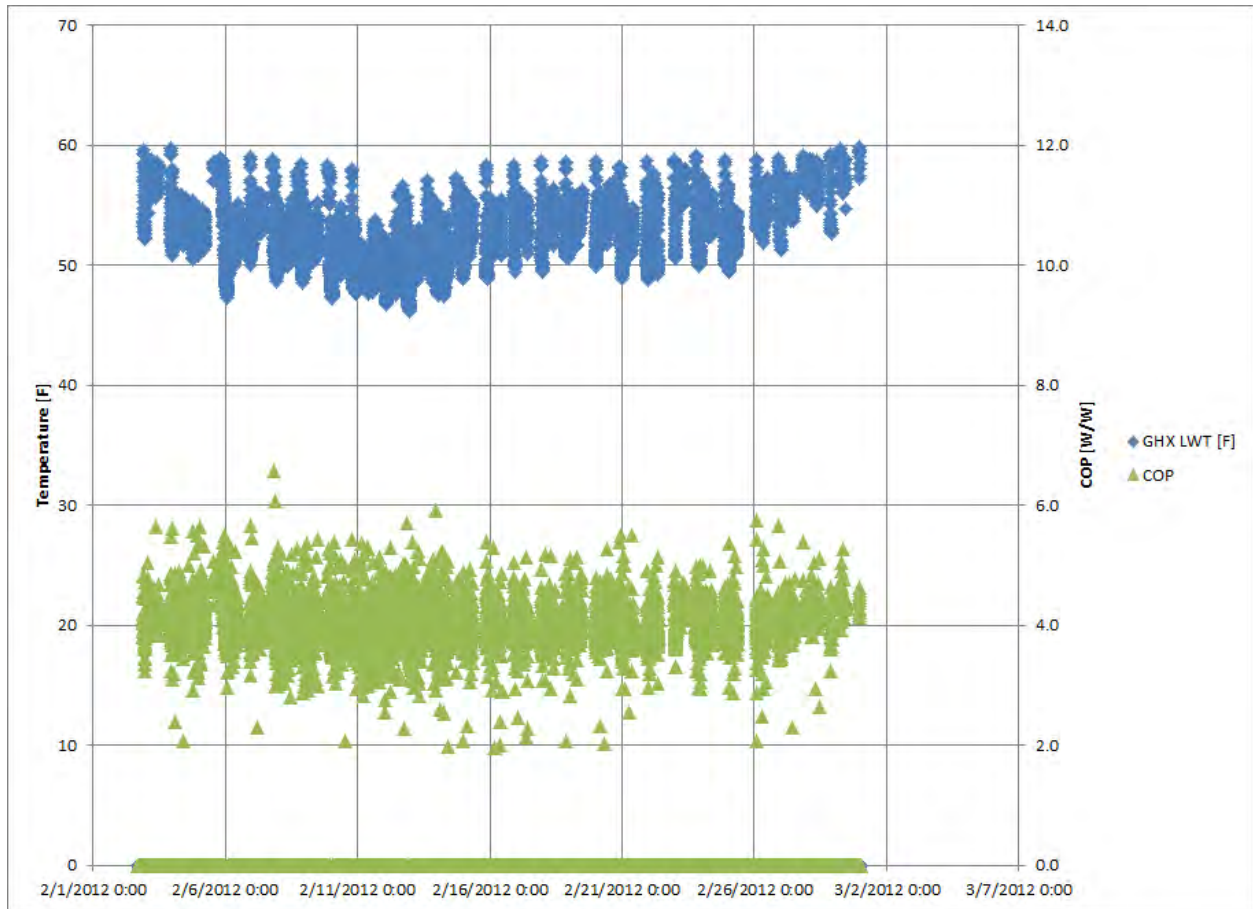


Figure B-3-10-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

B-4: JUNE 2012

Unit 01 (925)

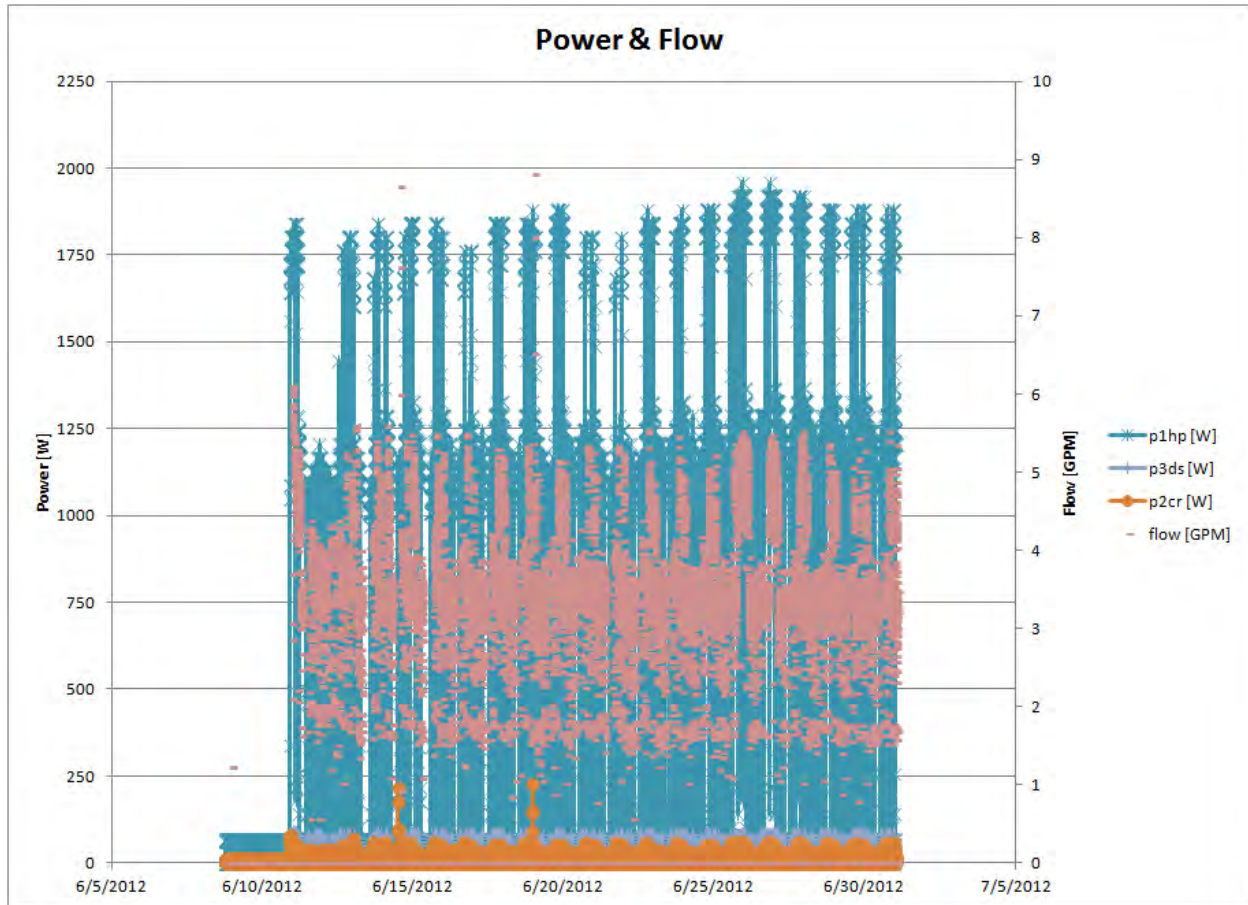


Figure B-4-1-1. Measured power and flow rate

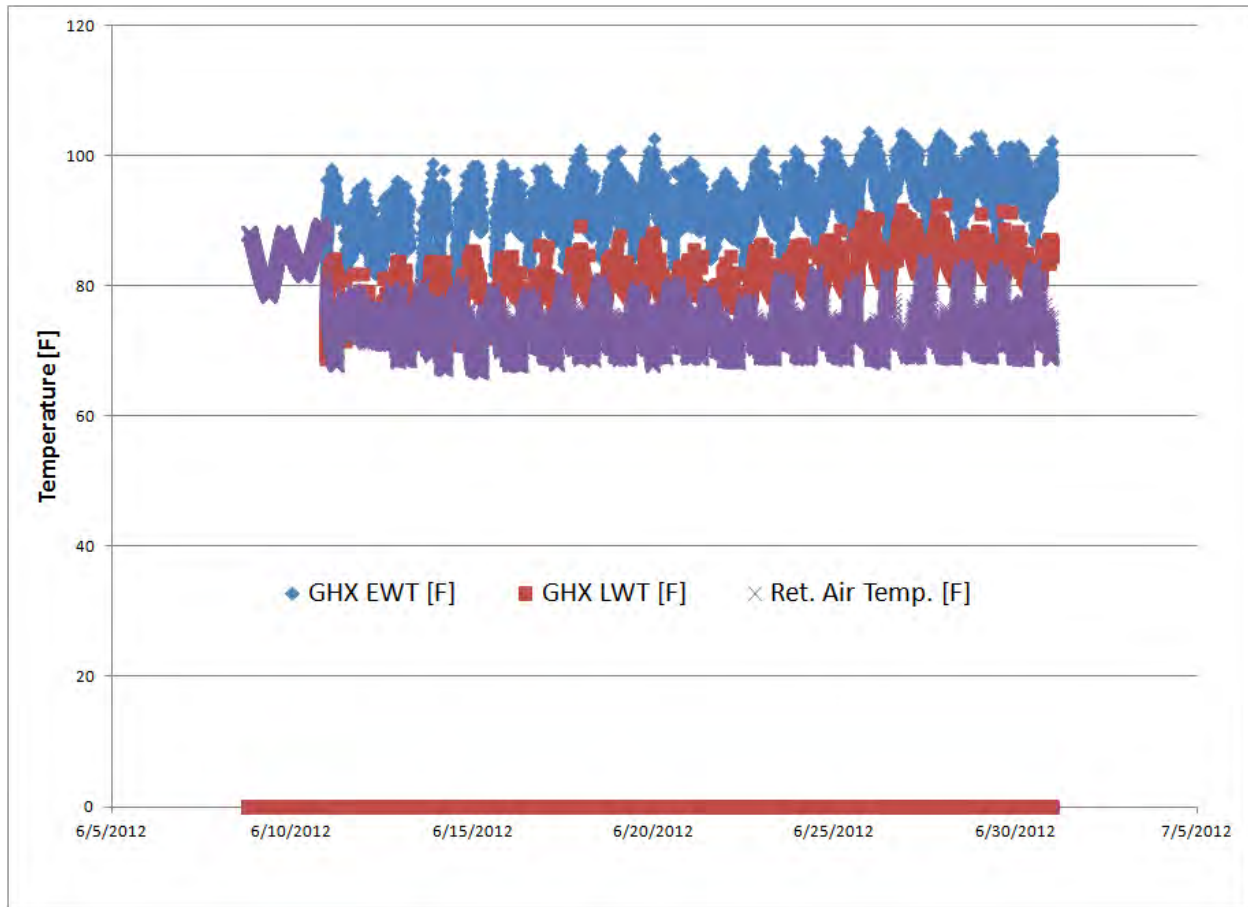


Figure B-4-1-2. Measured room and loop temperatures

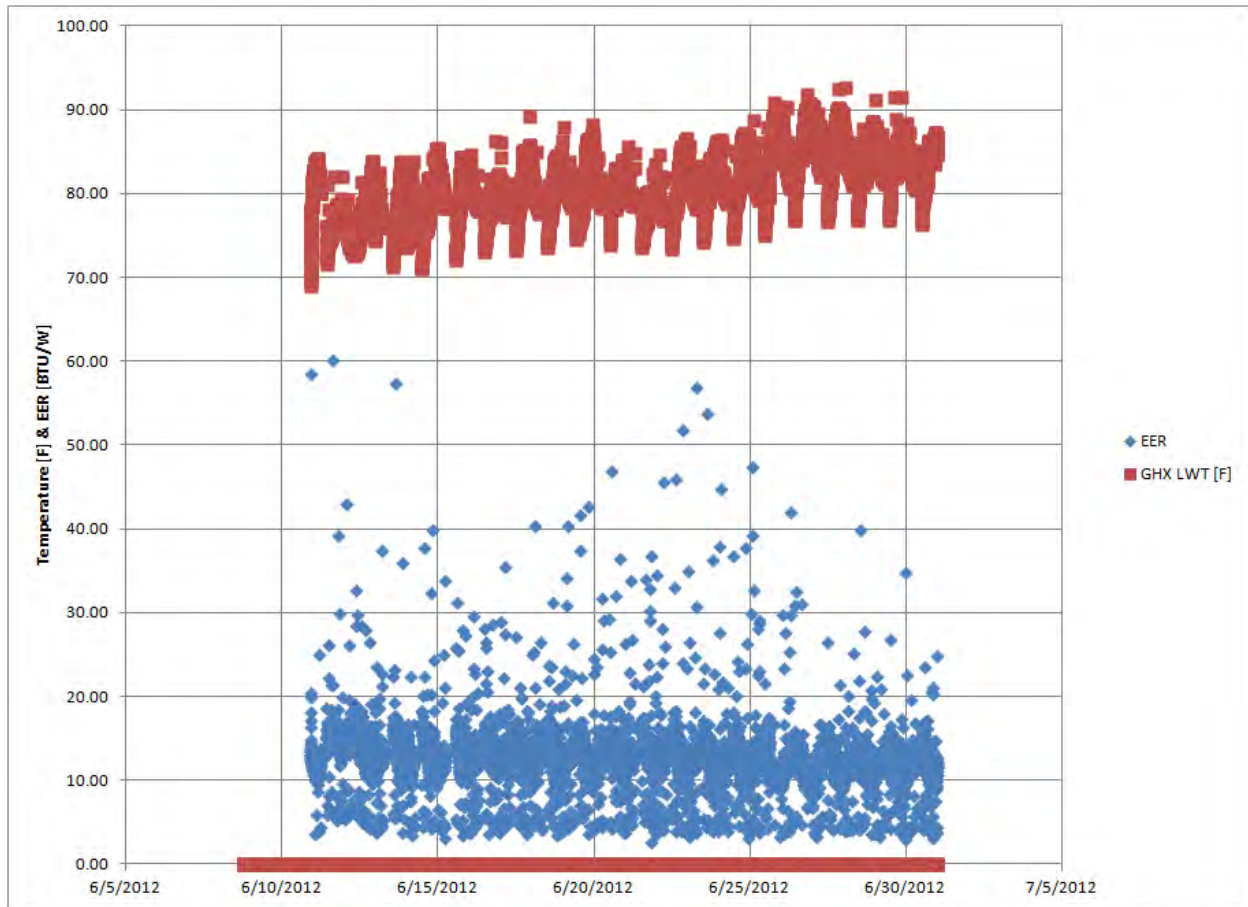


Figure B-4-1-3. Calculated system EER (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 02 (916)

Unit 2 has been disconnected since May, 2012 and no any data will be collected from this unit.

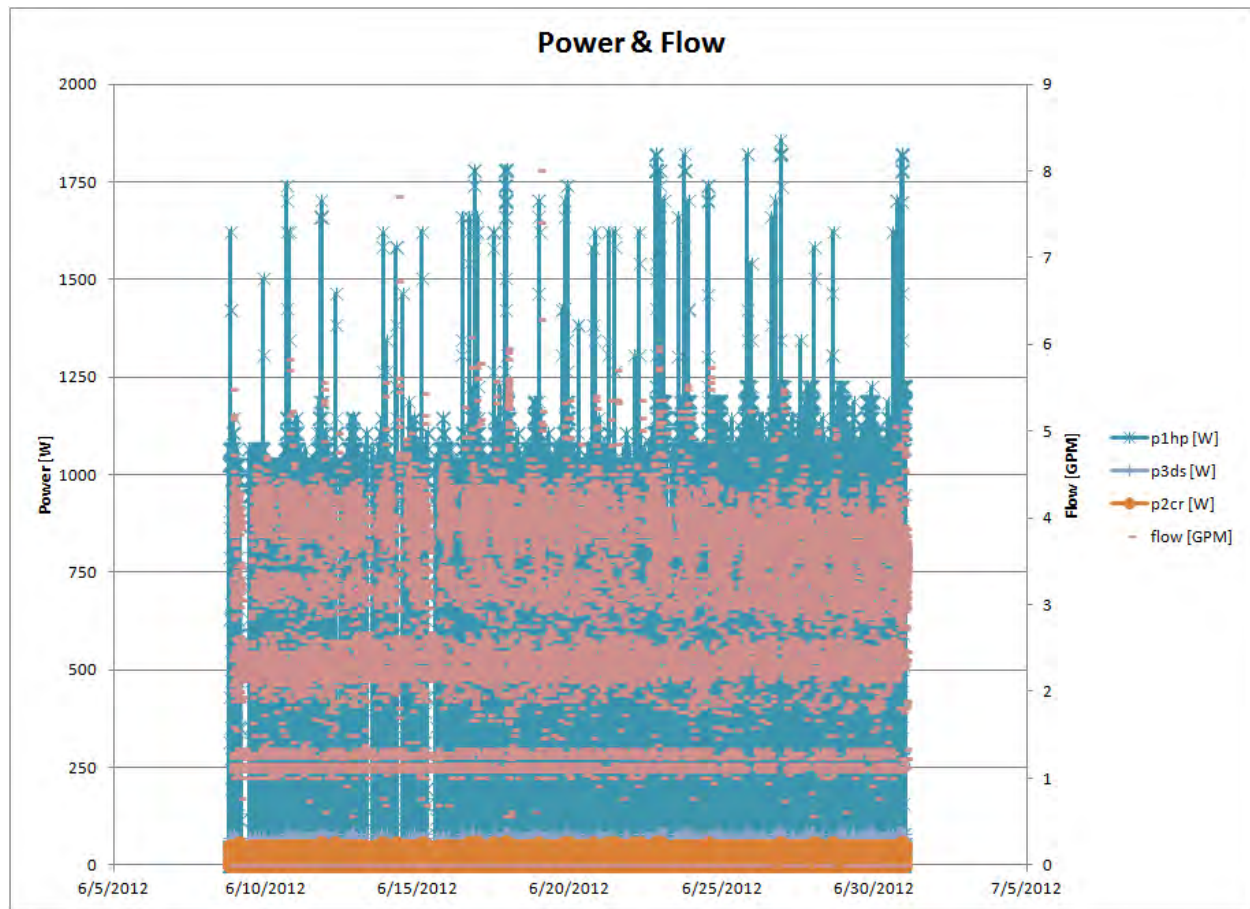


Figure B-4-3-1. Measured power and flow rate

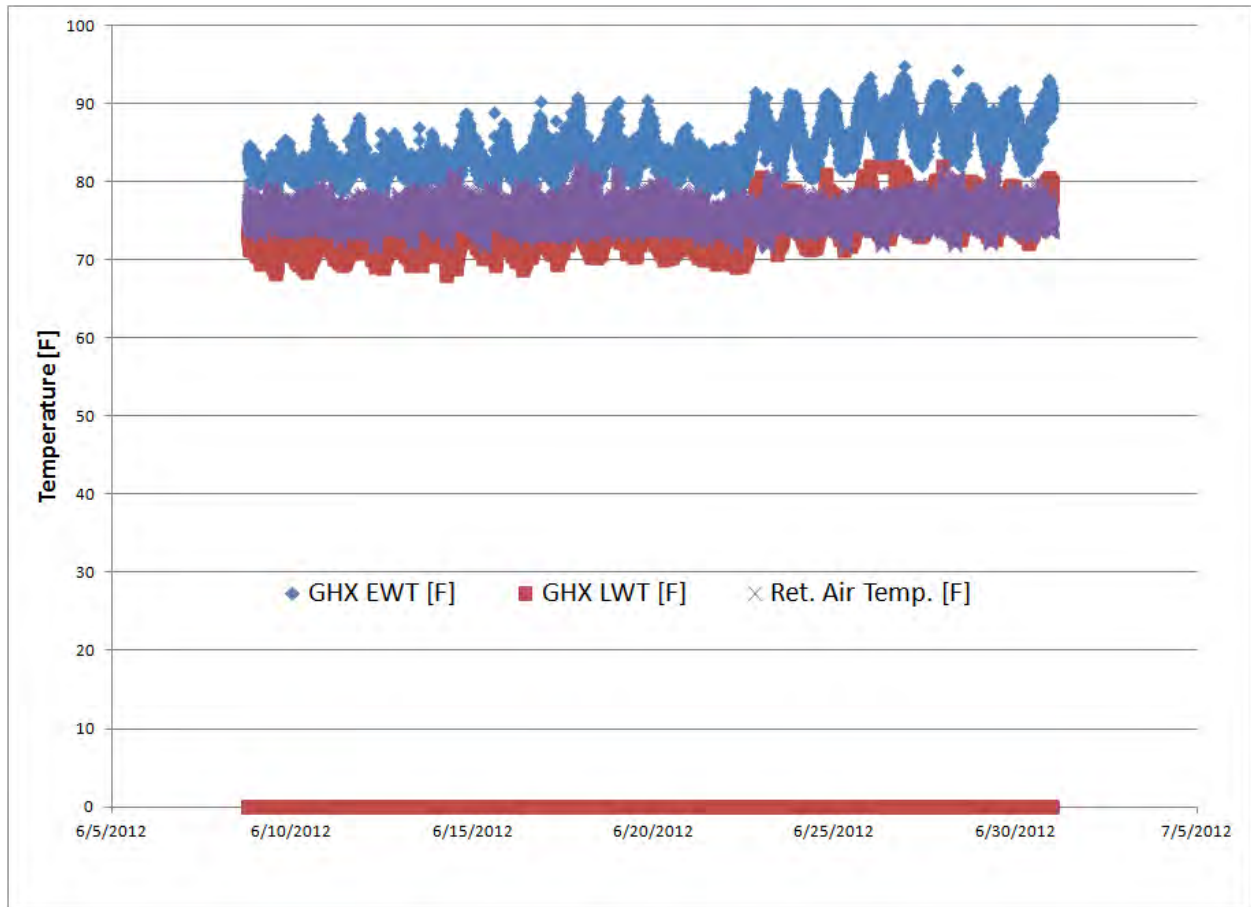


Figure B-4-3-2. Measured room and loop temperatures

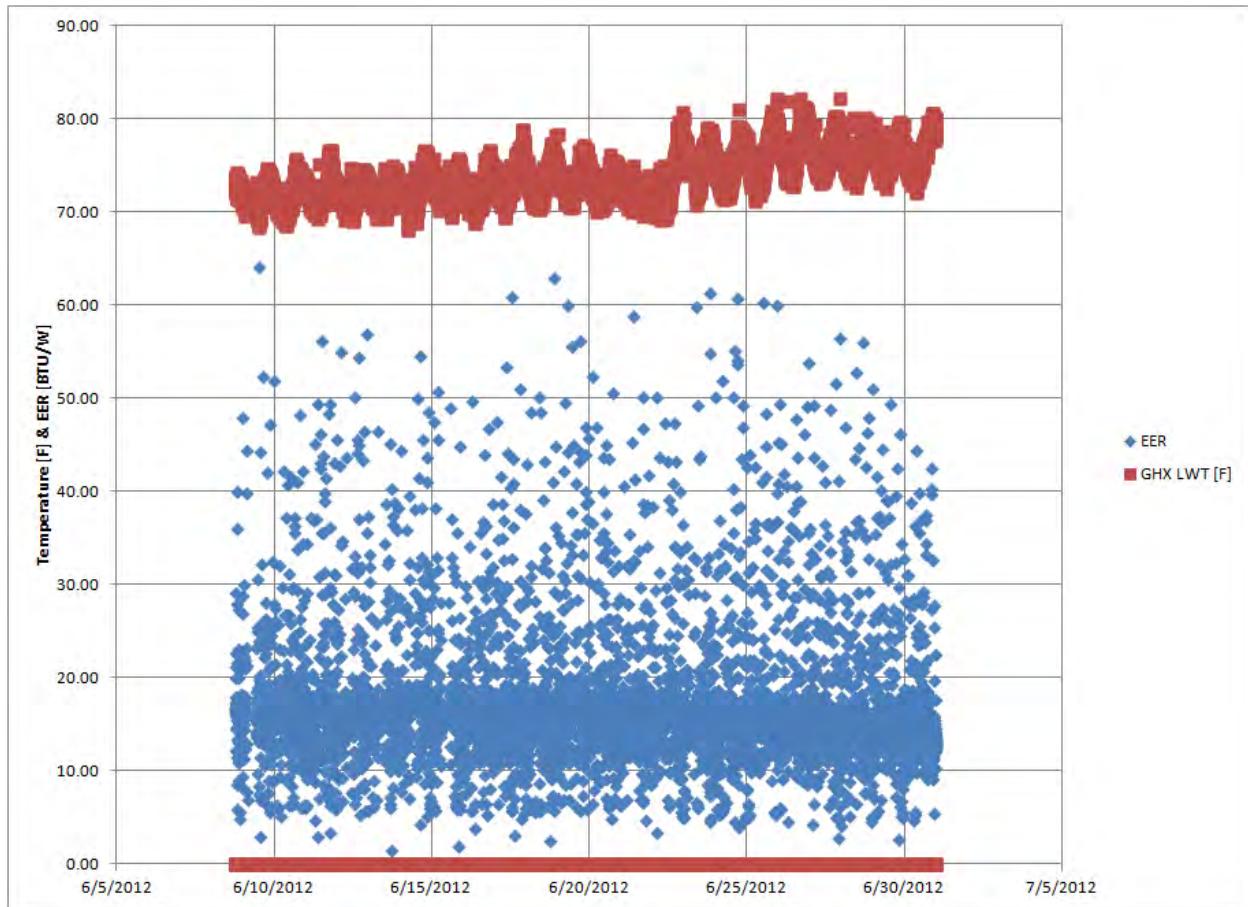


Figure B-4-3-3. Calculated system EER (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 04 (932)

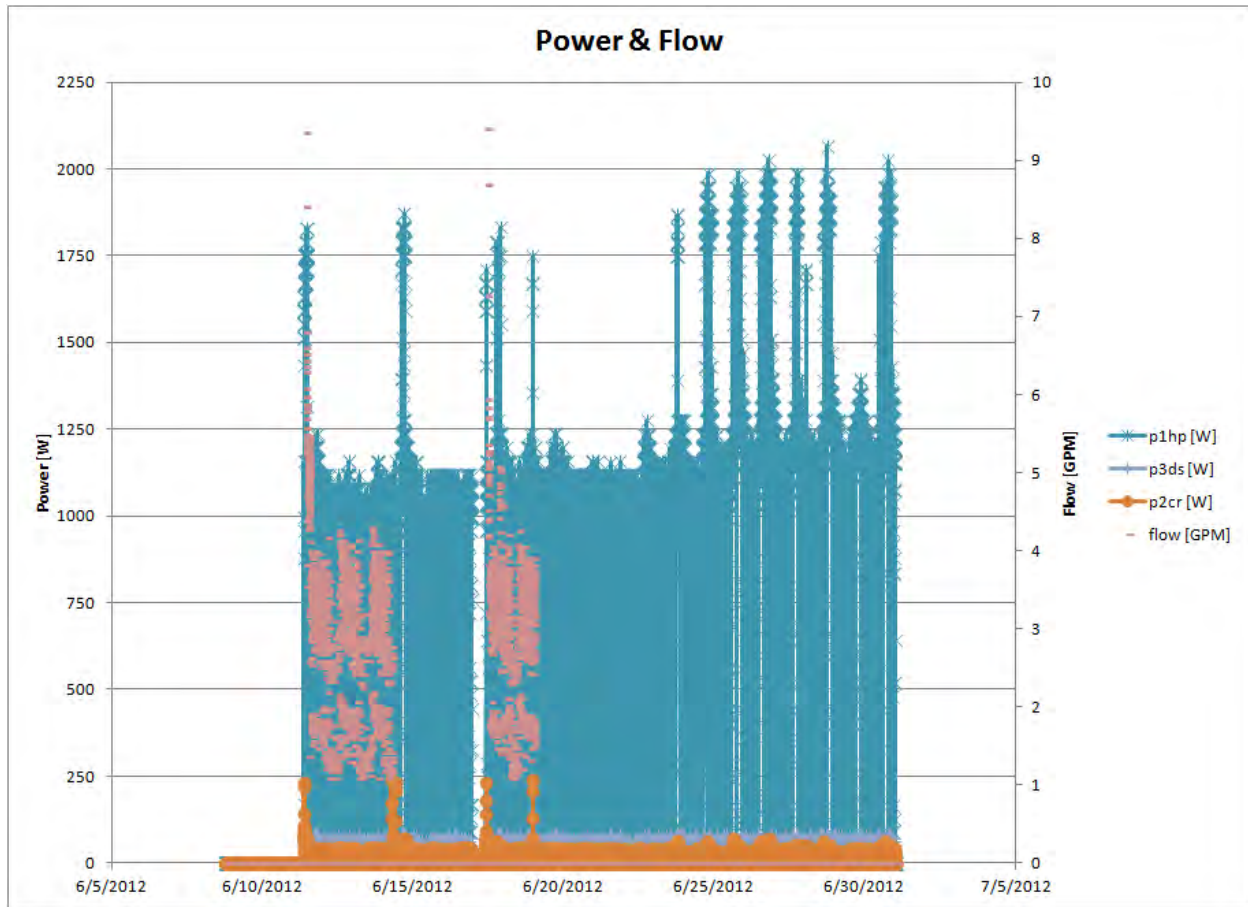


Figure B-4-4-1. Measured power and flow rate

9693 minutes (161 hours or 6.7 days) data is missing in this month.



Figure B-4-4-2. Measured room and loop temperatures

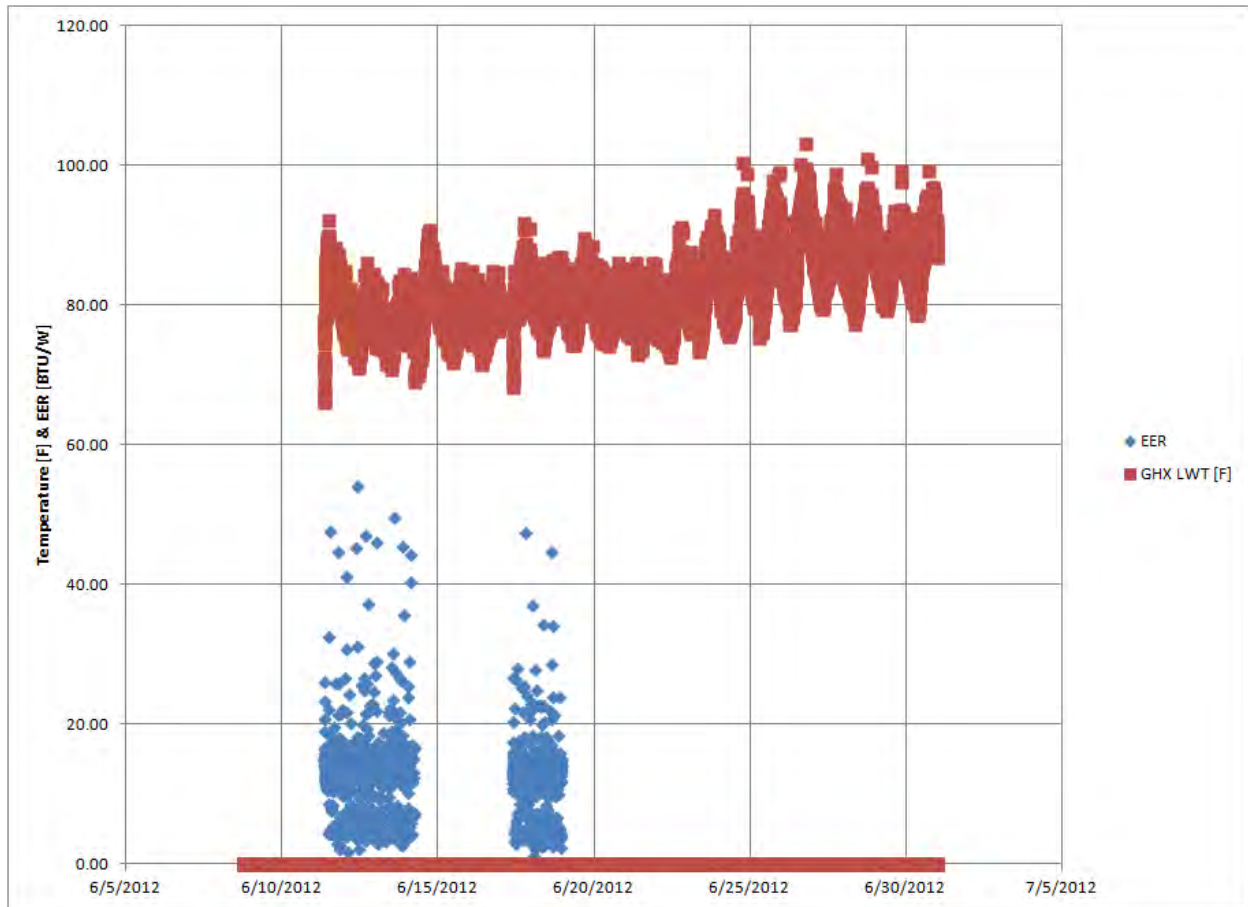


Figure B-4-4-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

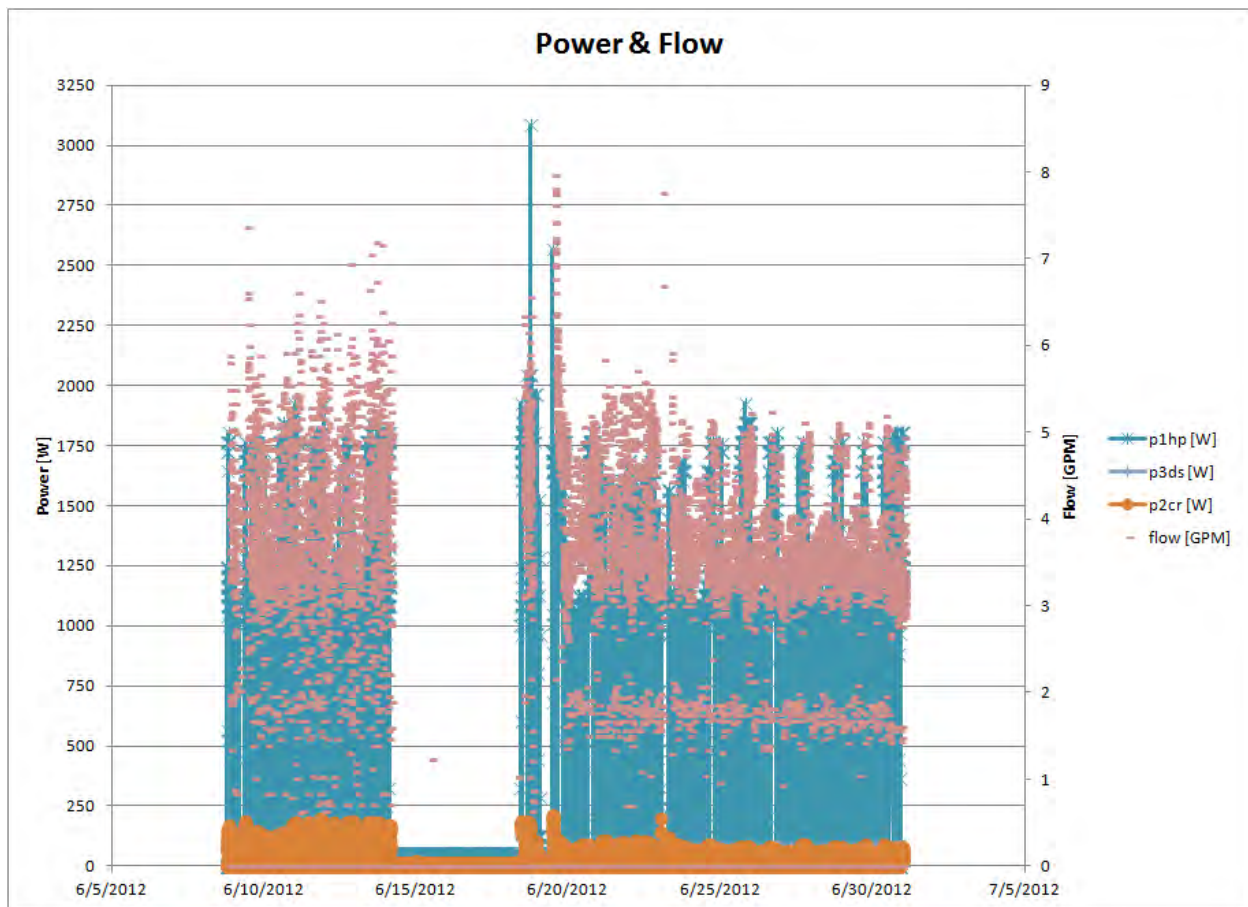


Figure B-4-5-1. Measured power and flow rate

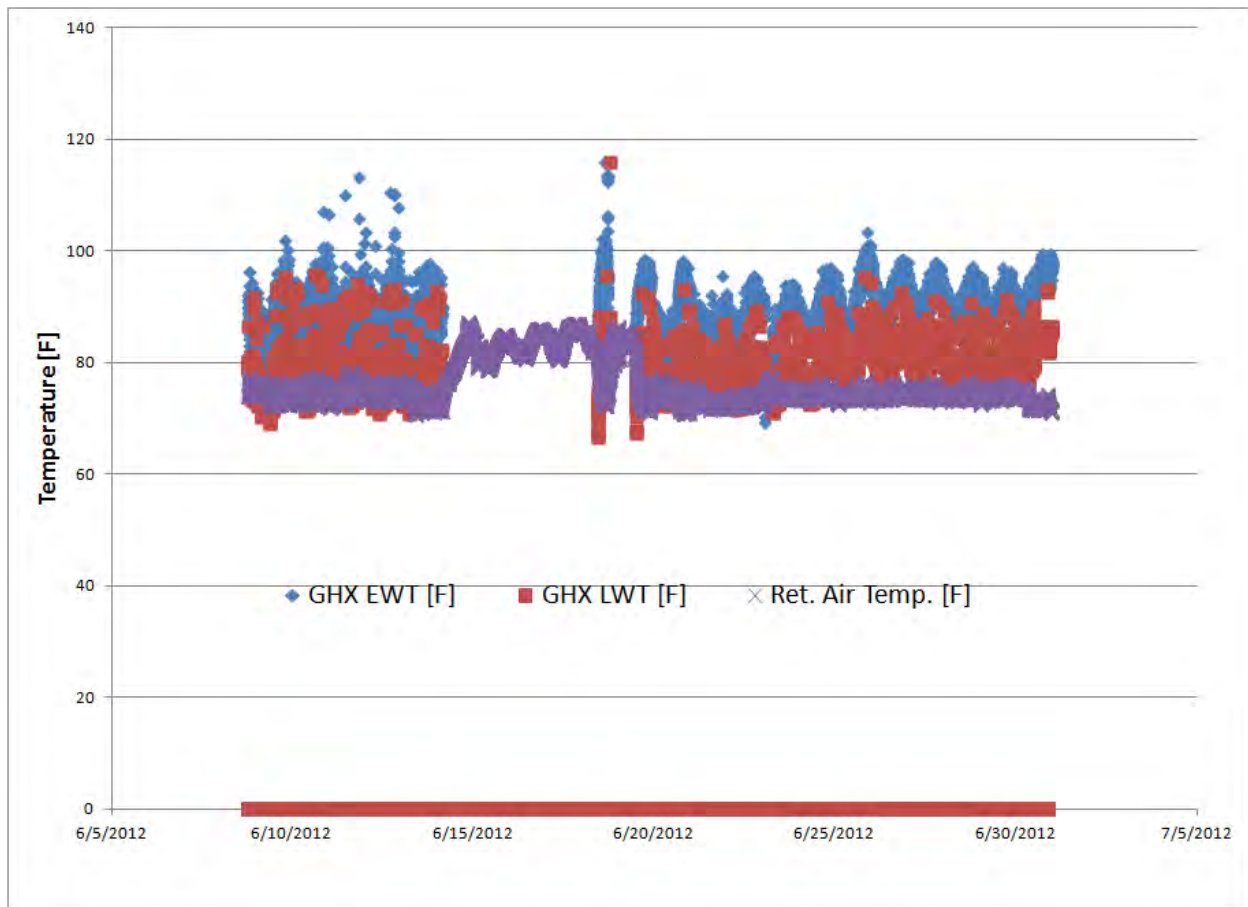


Figure B-4-5-2. Measured room and loop temperatures

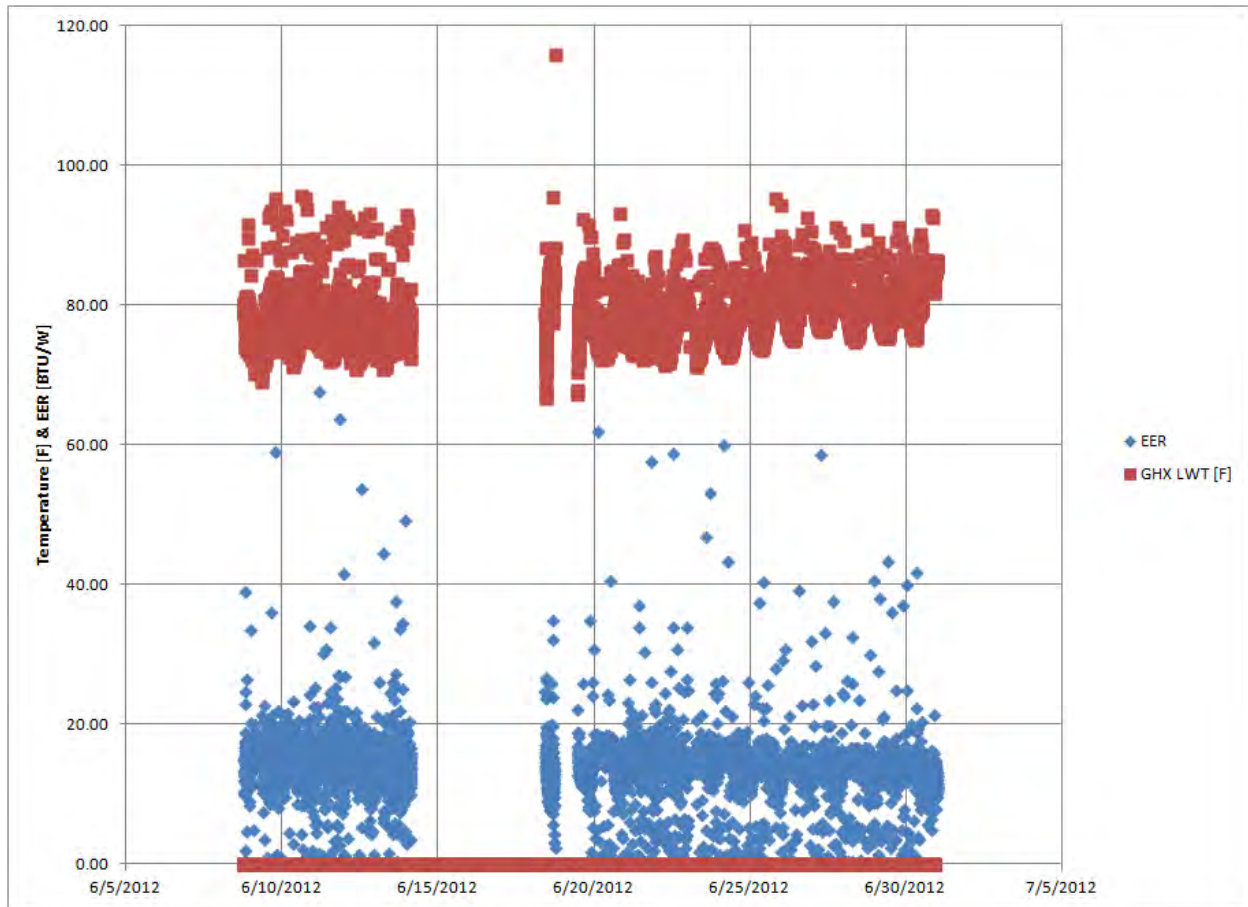


Figure B-4-5-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

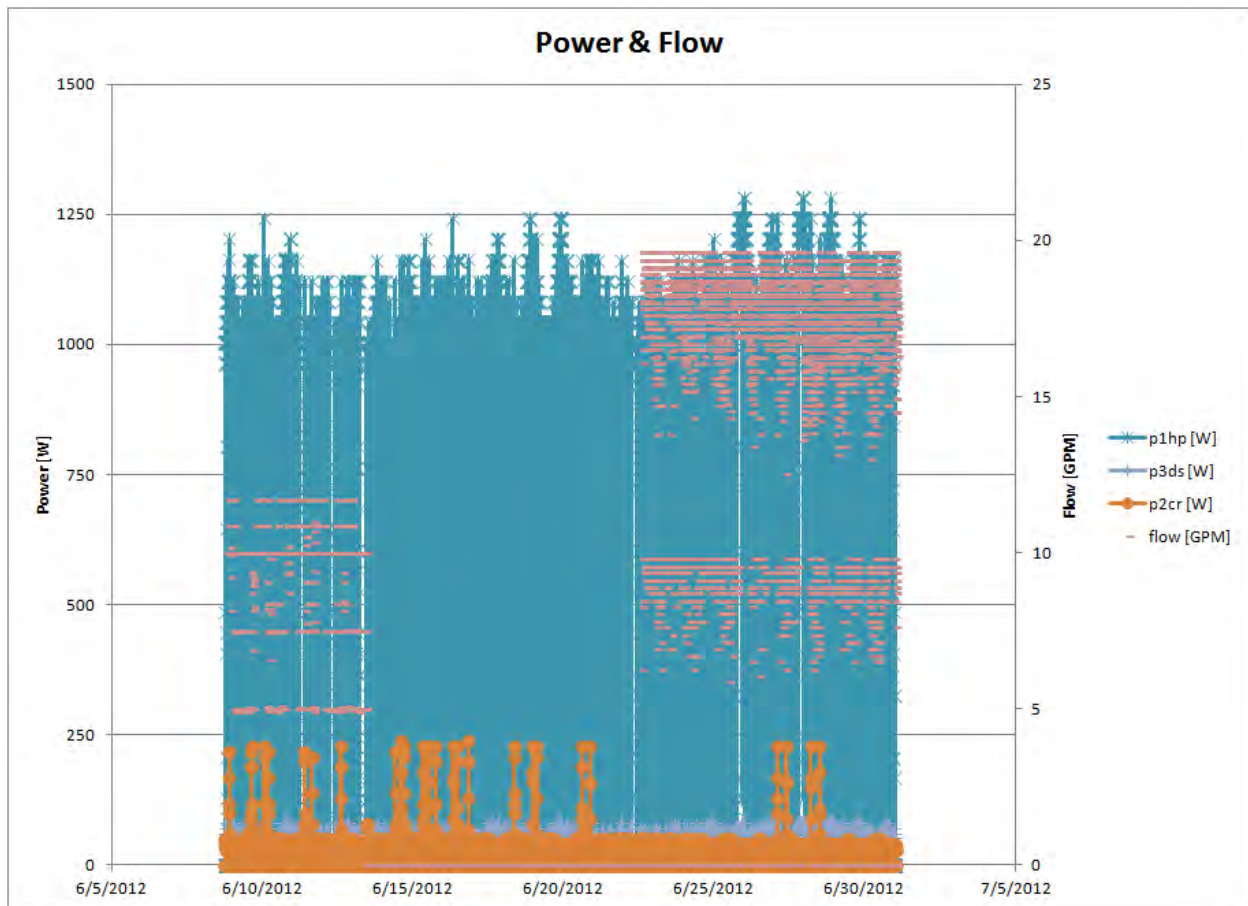


Figure B-4-6-1. Measured power and flow rate

9637 minutes (161 hours or 6.7 days) data is missing in this month.

Average flow rate is 12 GPM (excluding all the zero flow rate data). The high flow rate measurements are not valid since the cooling/heating capacity calculated with the measured flow rate is more than double the nominal capacity of the 2 ton heat pump unit.



Figure B-4-6-2. Measured room and loop temperatures

Unit 07 (928)

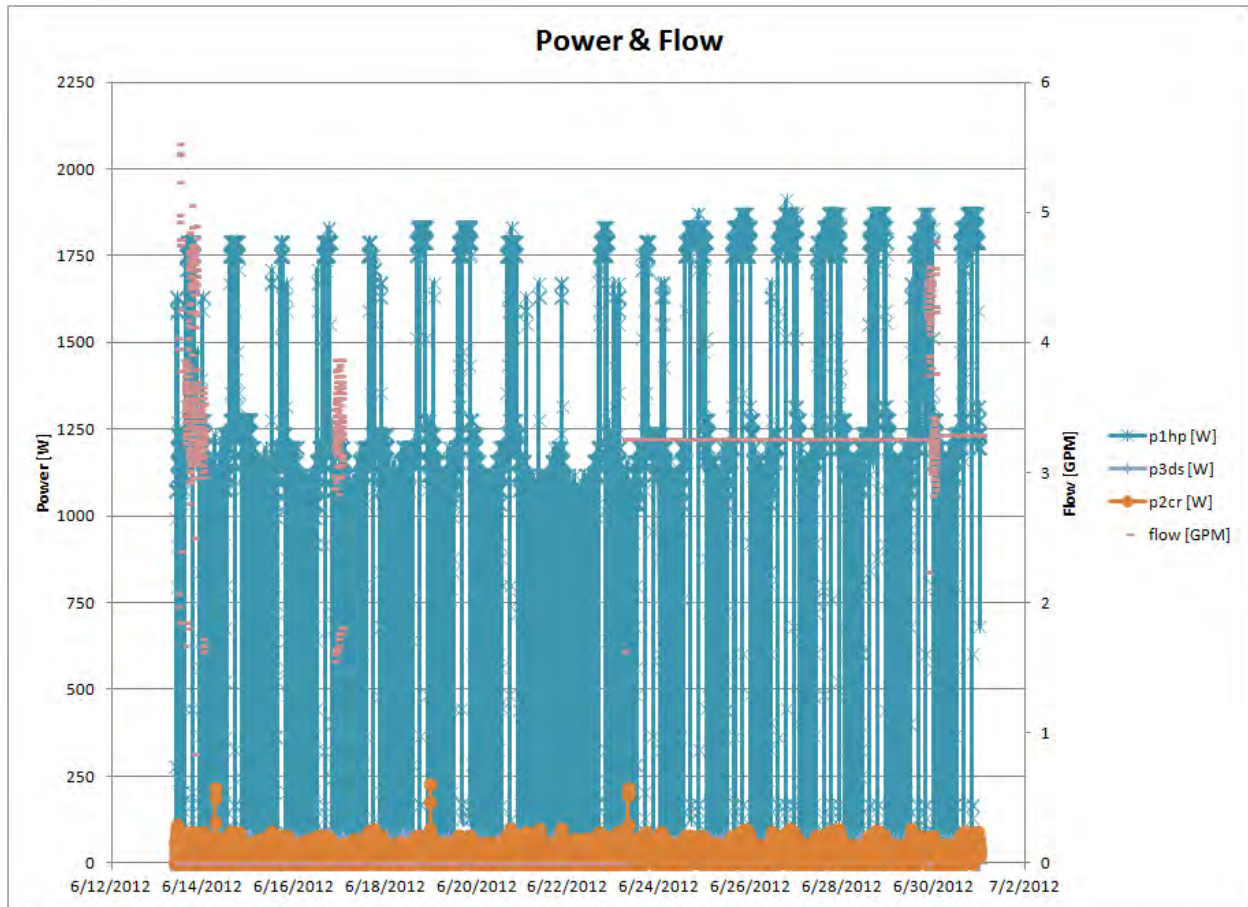


Figure B-4-7-1. Measured power and flow rate

17855 minutes (298 hours or 12.4 days) data is missing in this month.

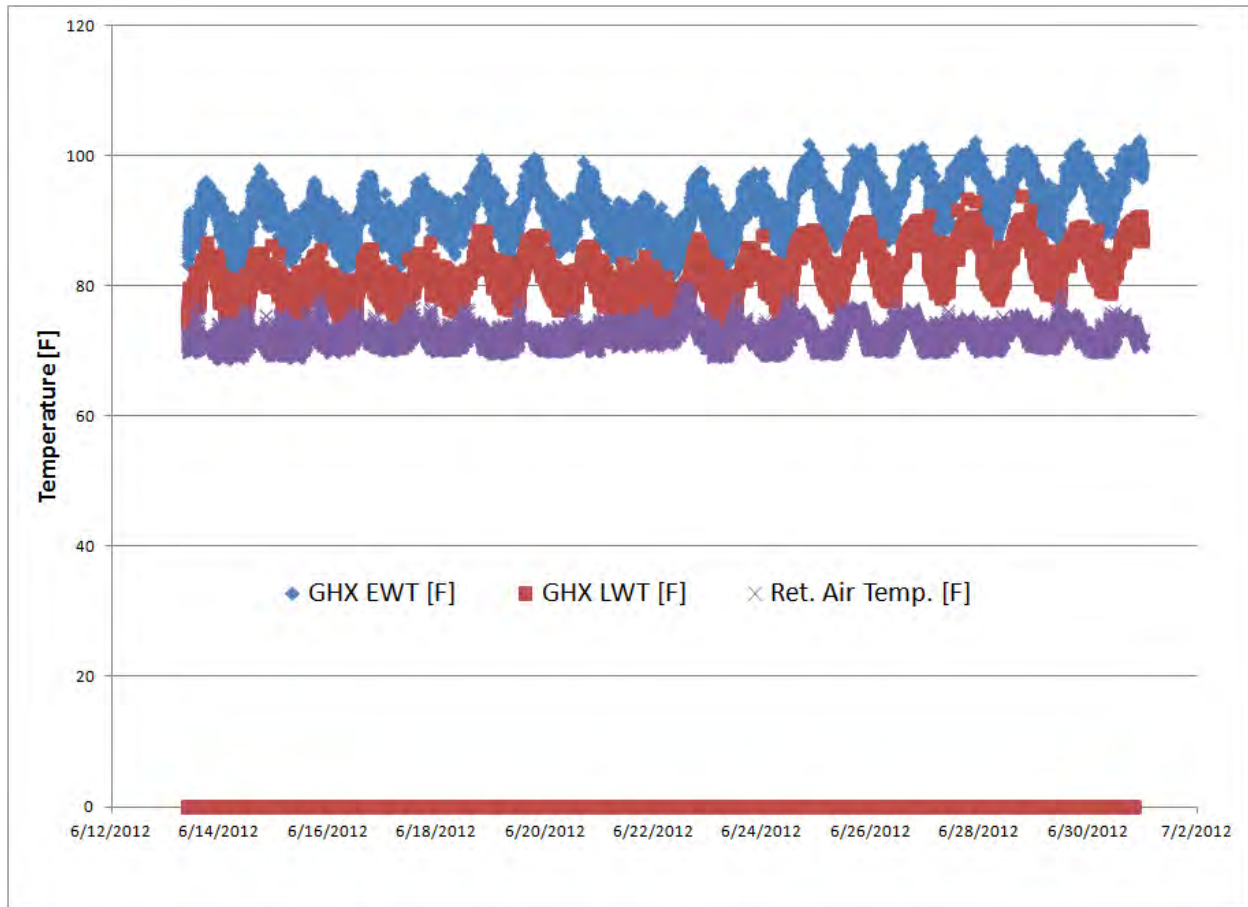


Figure B-4-7-2. Measured room and loop temperatures

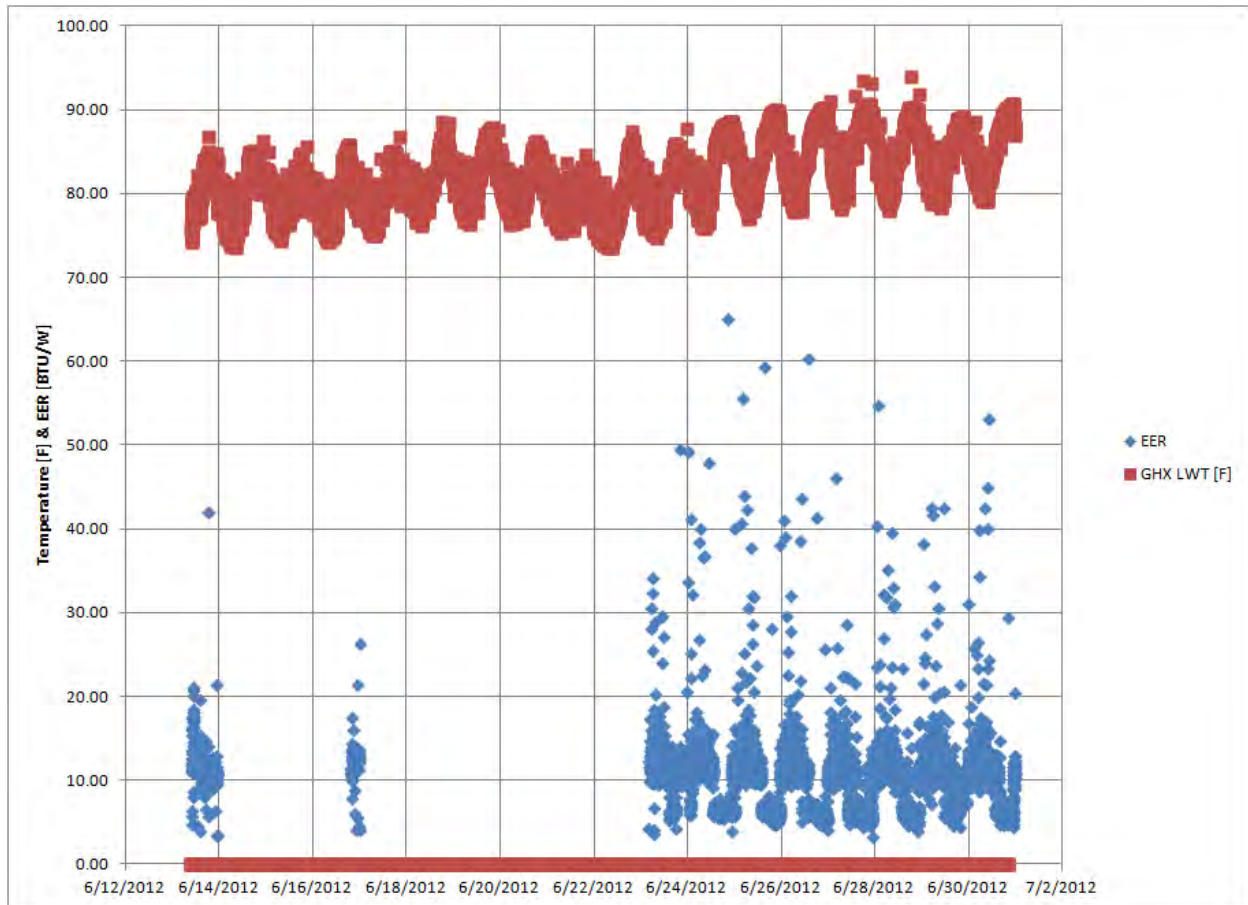


Figure B-4-7-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

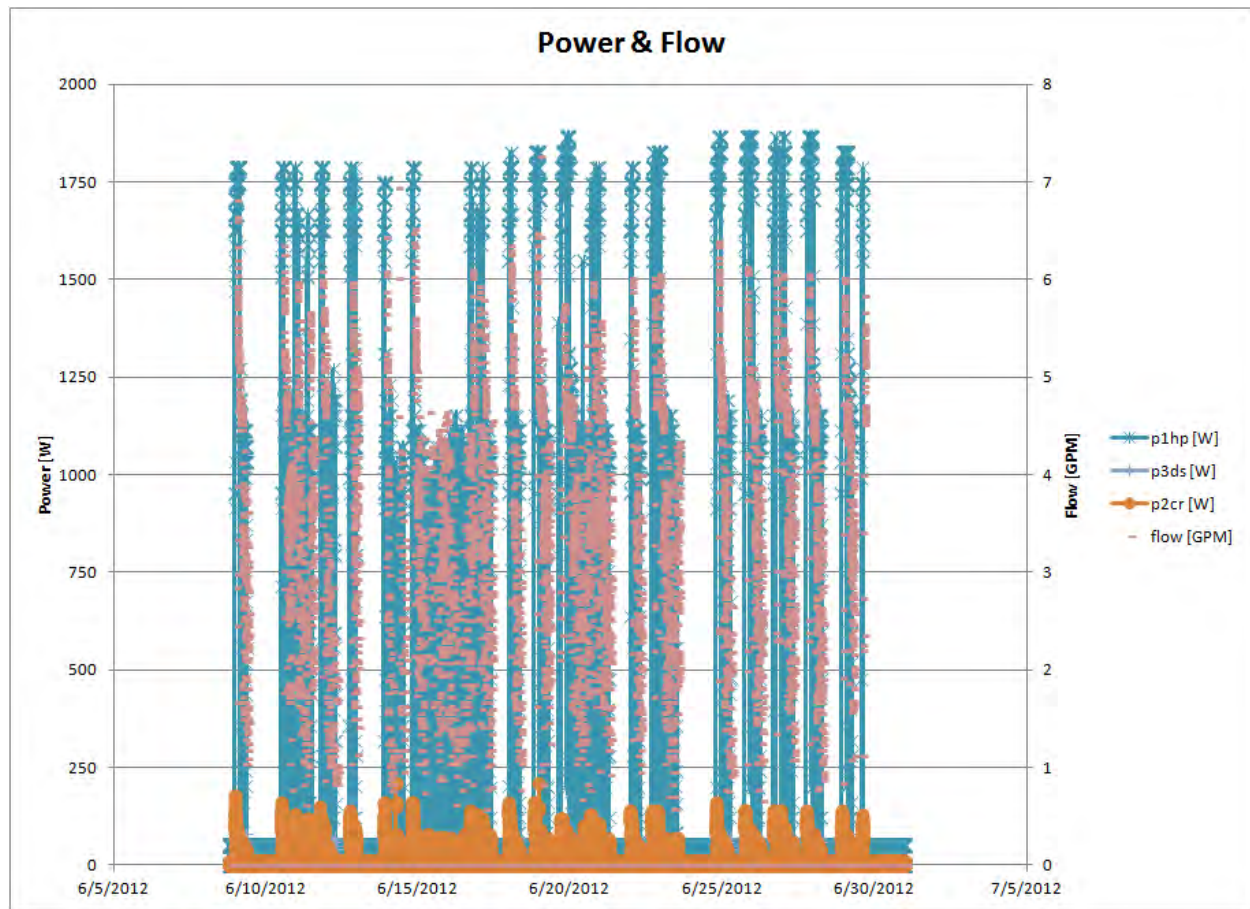


Figure B-4-8-1. Measured power and flow rate

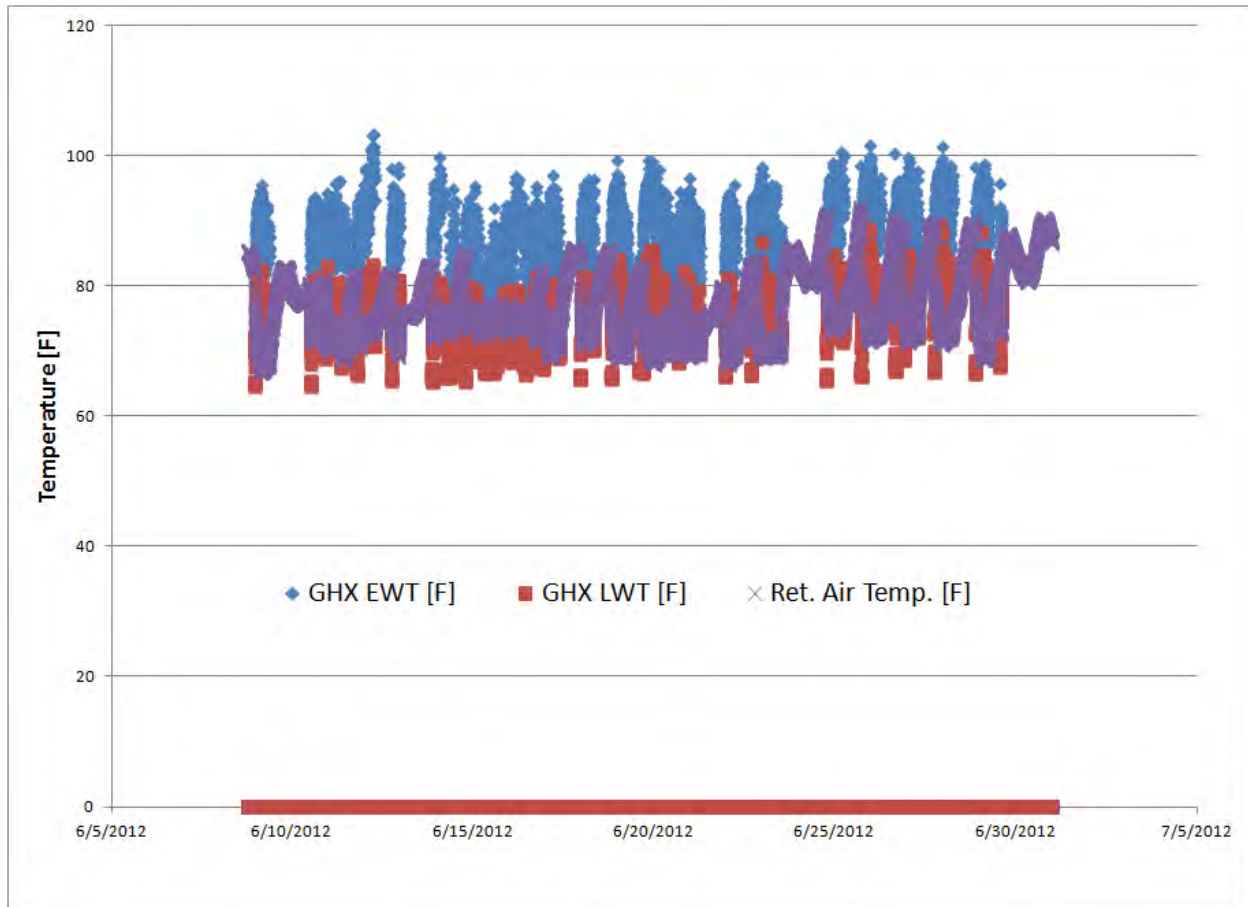


Figure B-4-8-2. Measured room and loop temperatures

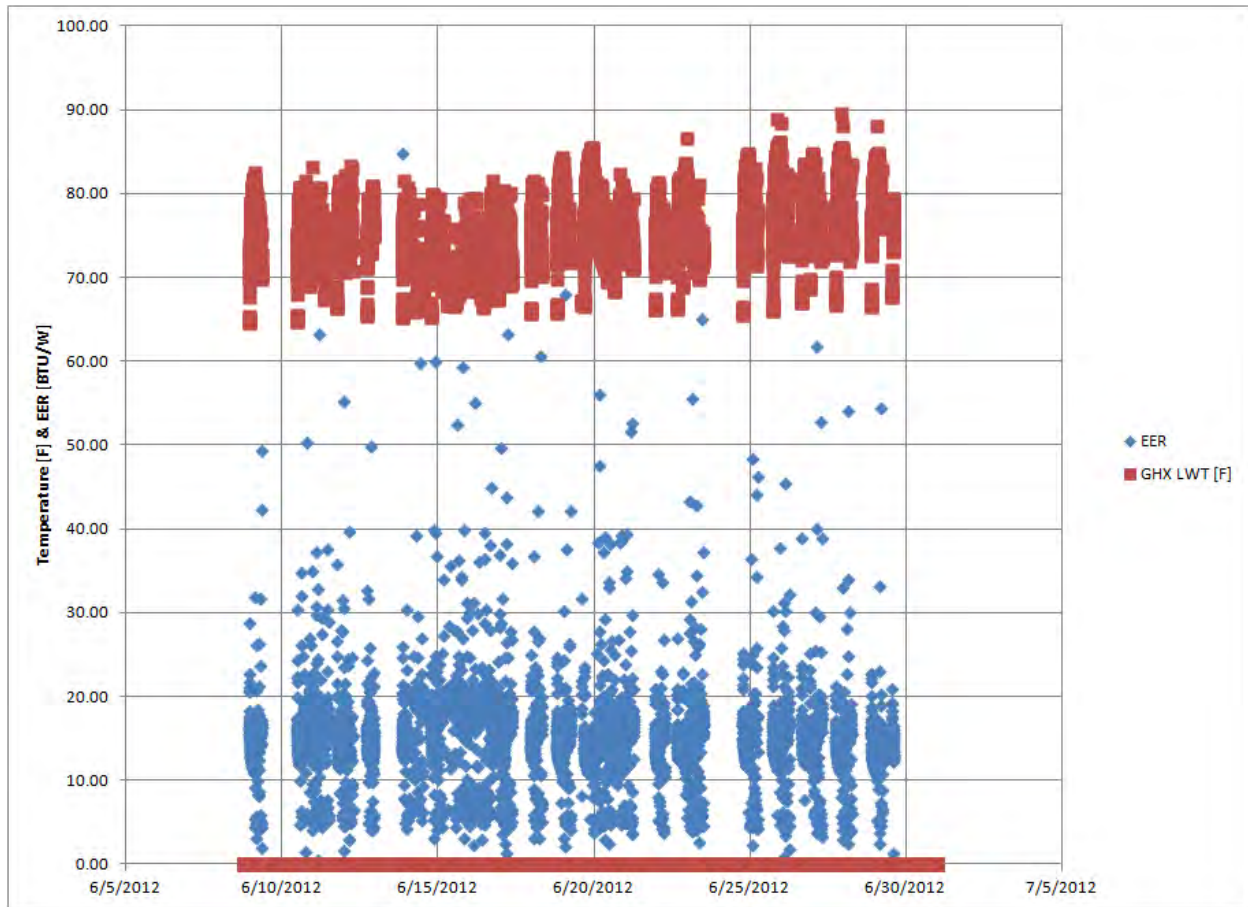


Figure B-4-8-3. Calculated system EER (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 09 (944)

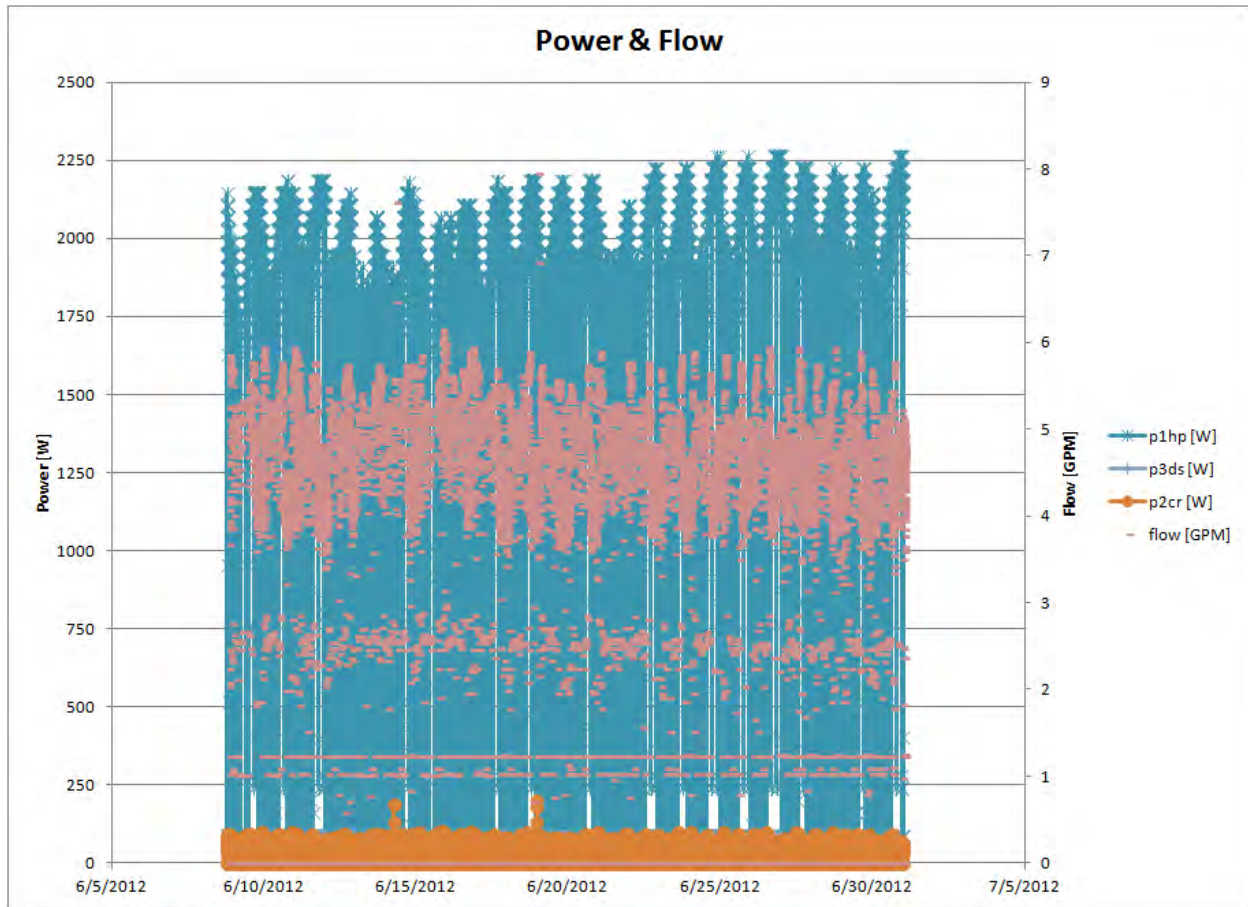


Figure B-4-9-1. Measured power and flow rate

9671 minutes (161 hours or 6.7 days) data is missing in this month.

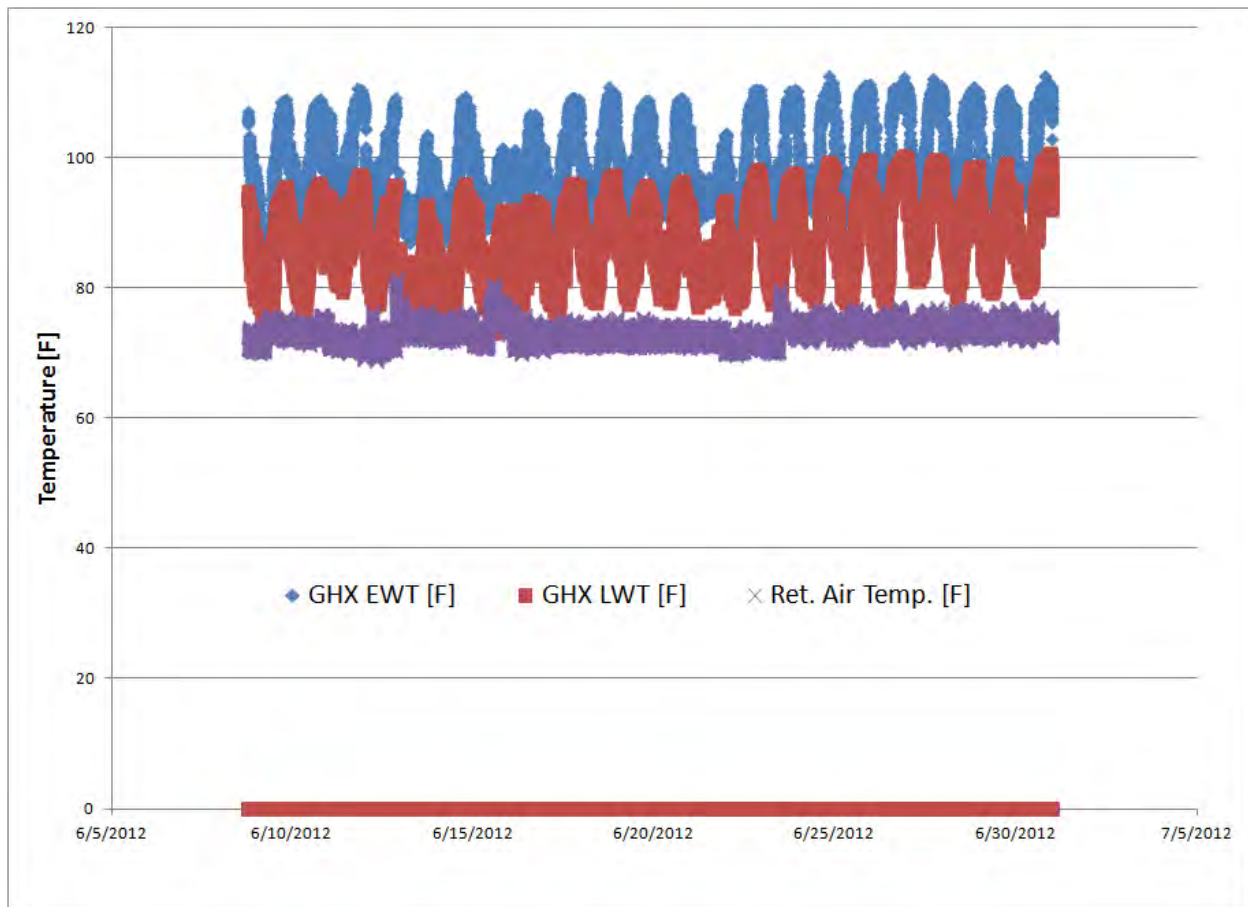


Figure B-4-9-2. Measured room and loop temperatures

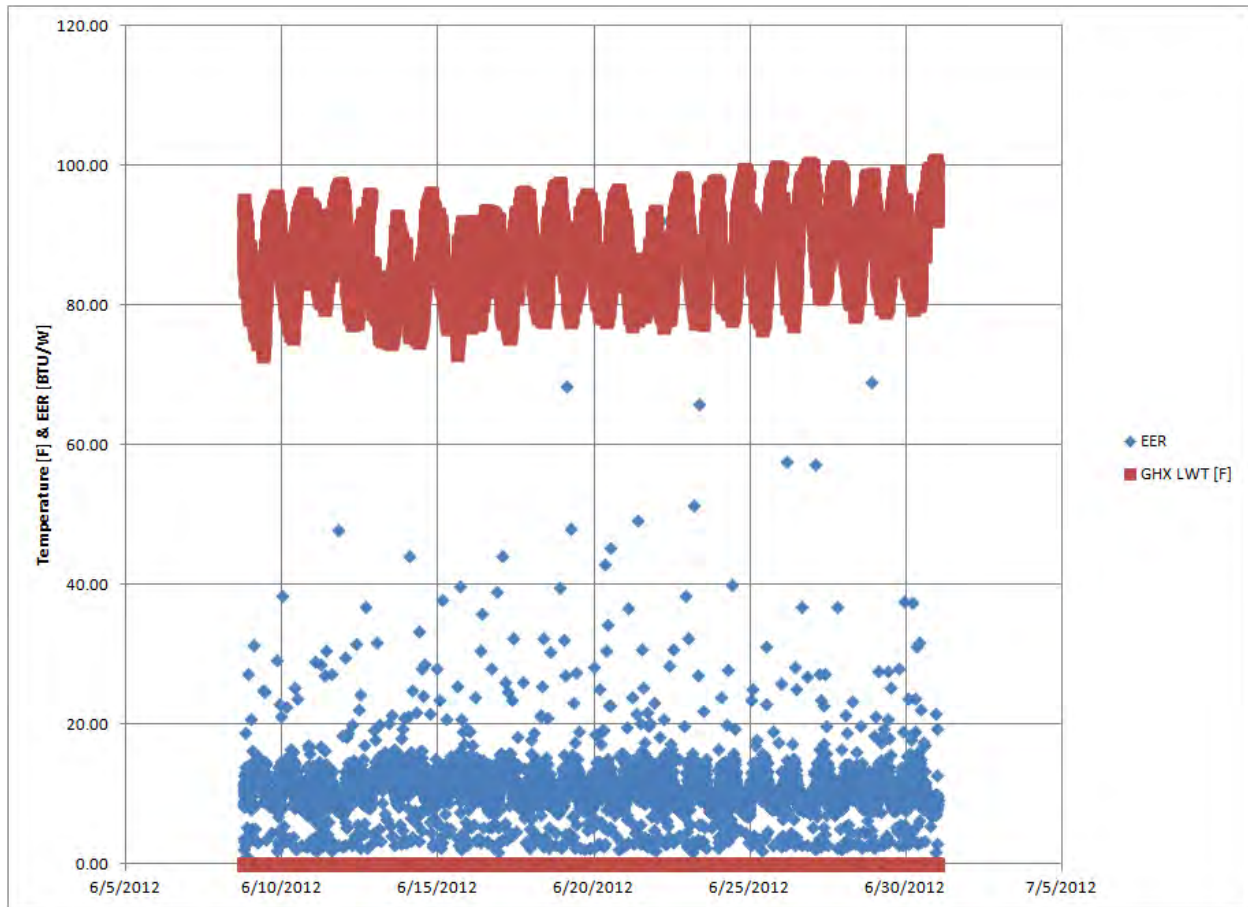


Figure B-4-9-3. Calculated system EER (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 10 (8528)

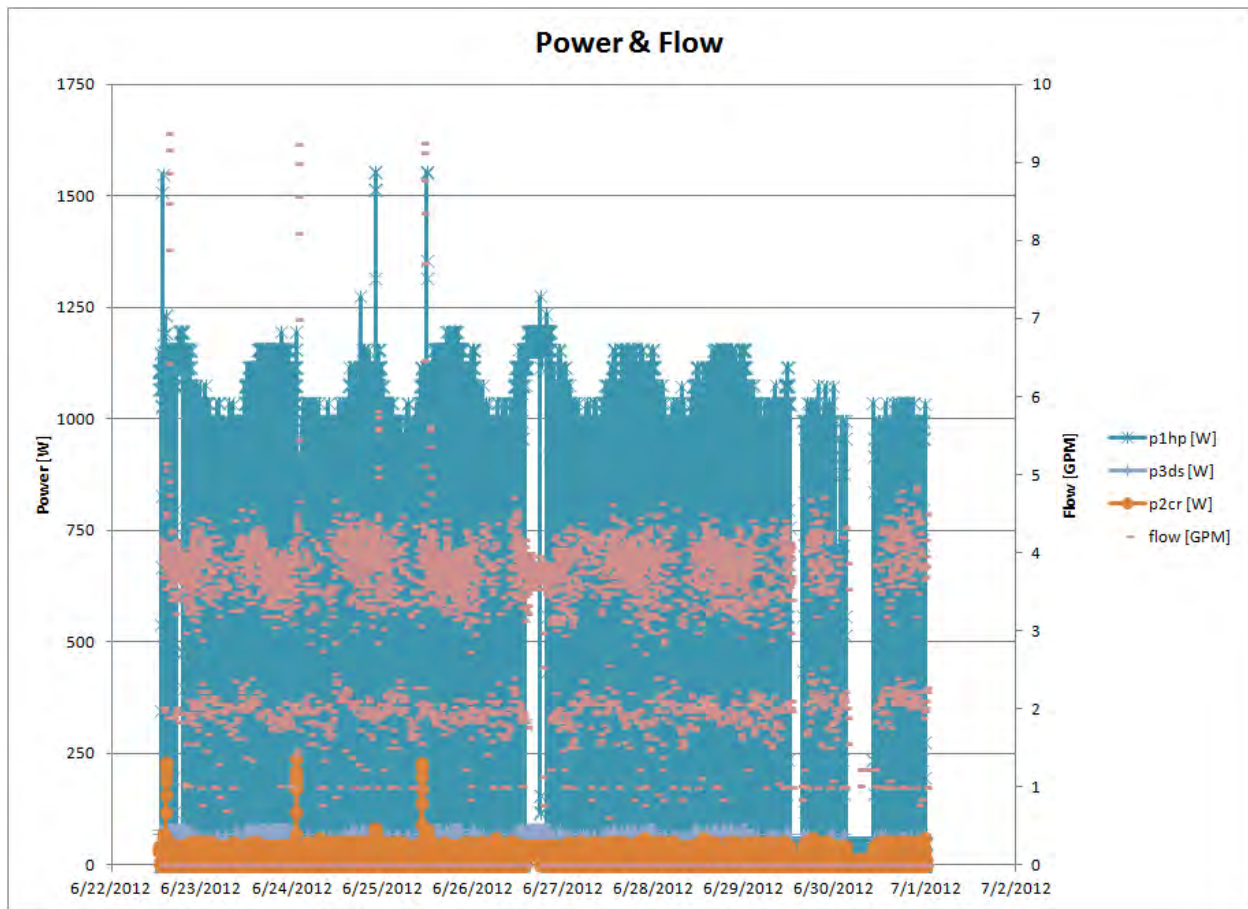


Figure B-4-10-1. Measured power and flow rate

30999 minutes (517 hours or 21.5 days) data is missing in this month. The above chart shows data only from 6/23/2012 to 7/1/2012.

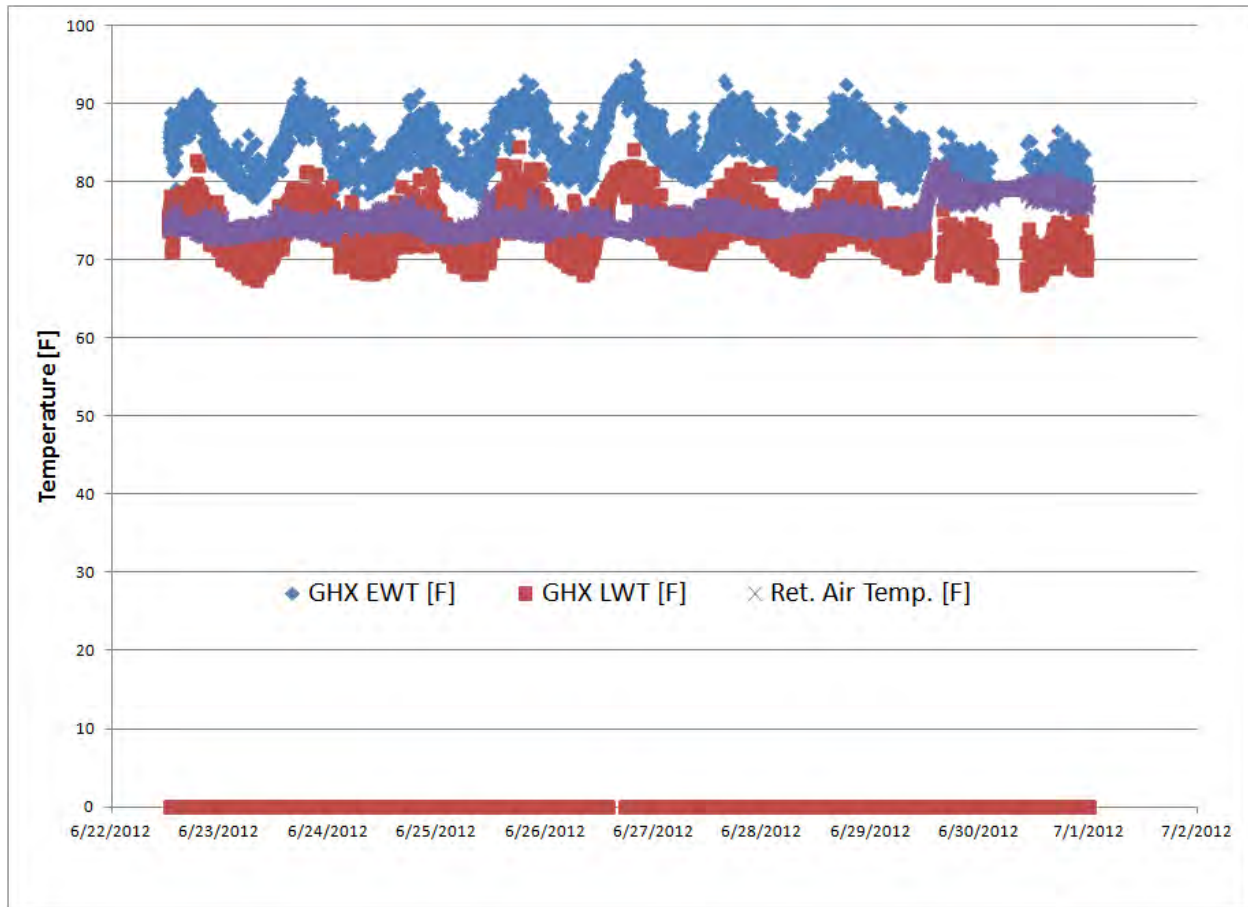


Figure B-4-10-2. Measured room and loop temperatures

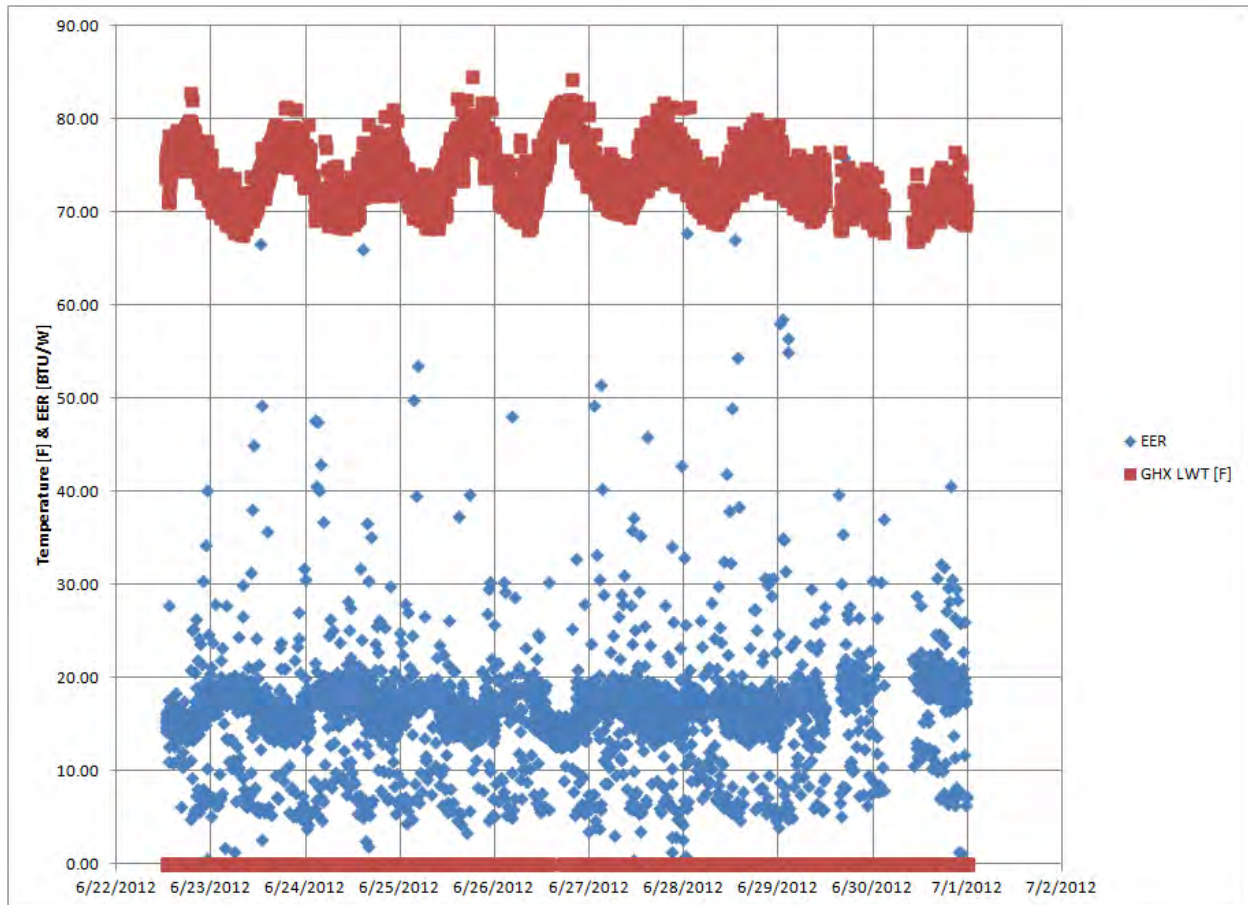


Figure B-4-10-3. Calculated system EER (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

B-5: JULY 2012

Unit 01 (925)

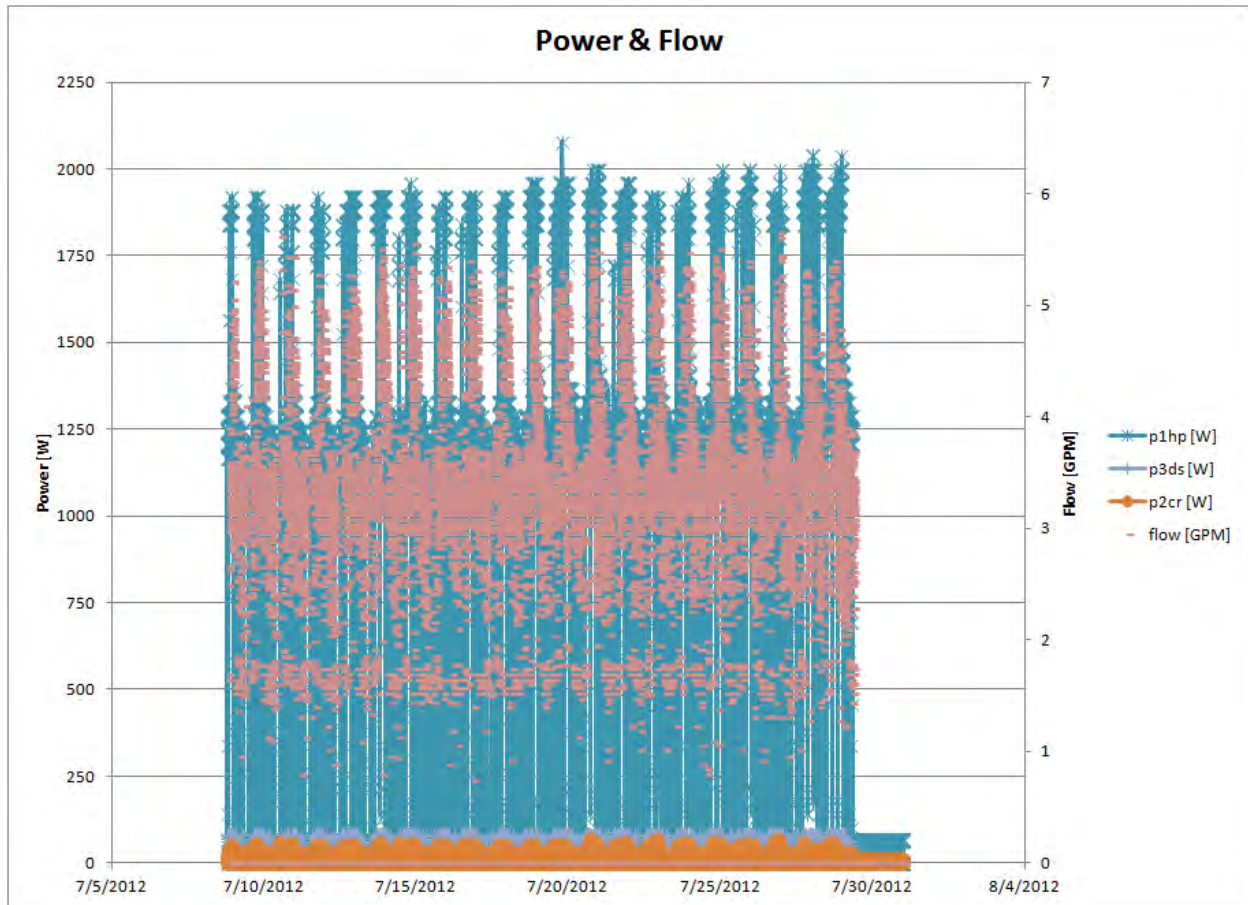


Figure B-5-1-1. Measured power and flow rate

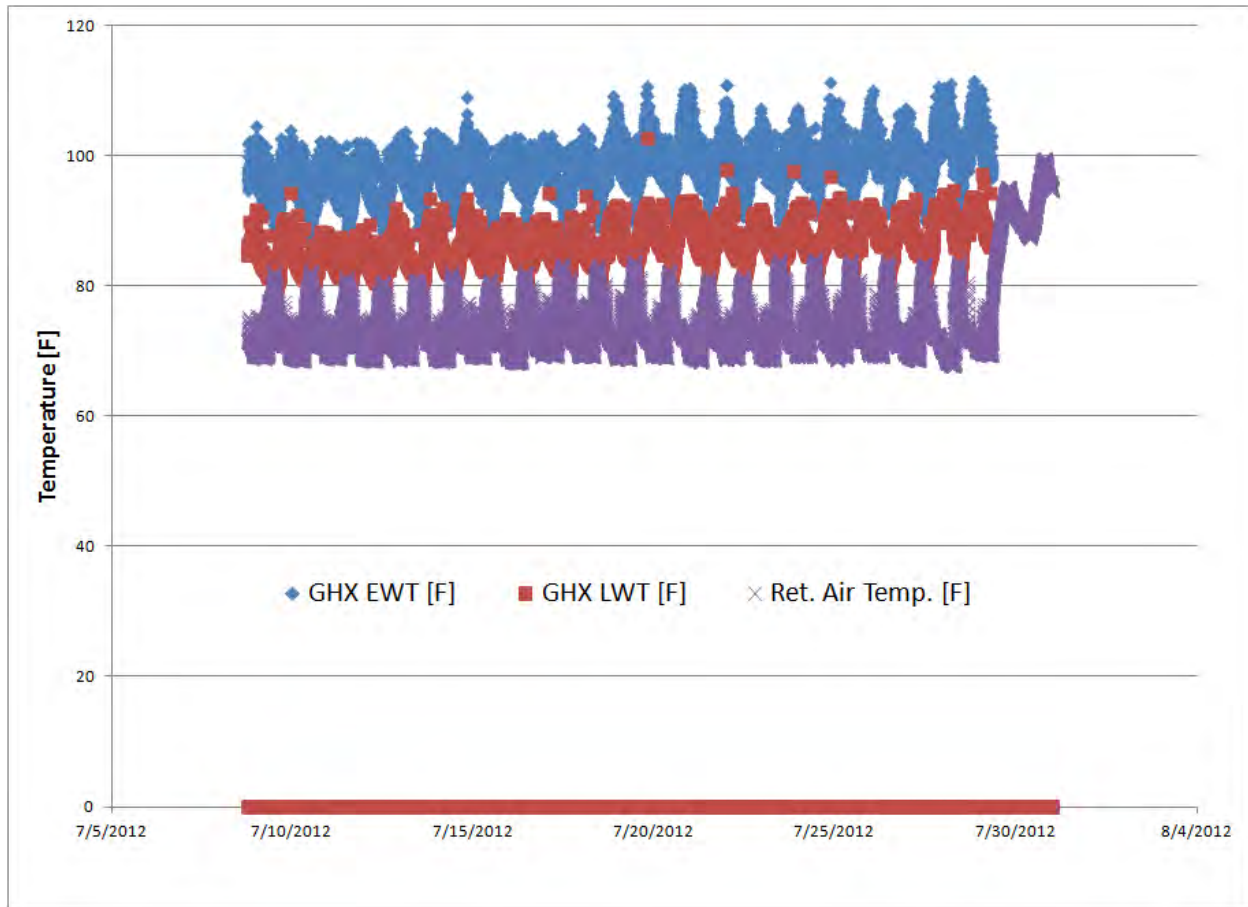


Figure B-5-1-2. Measured room and loop temperatures

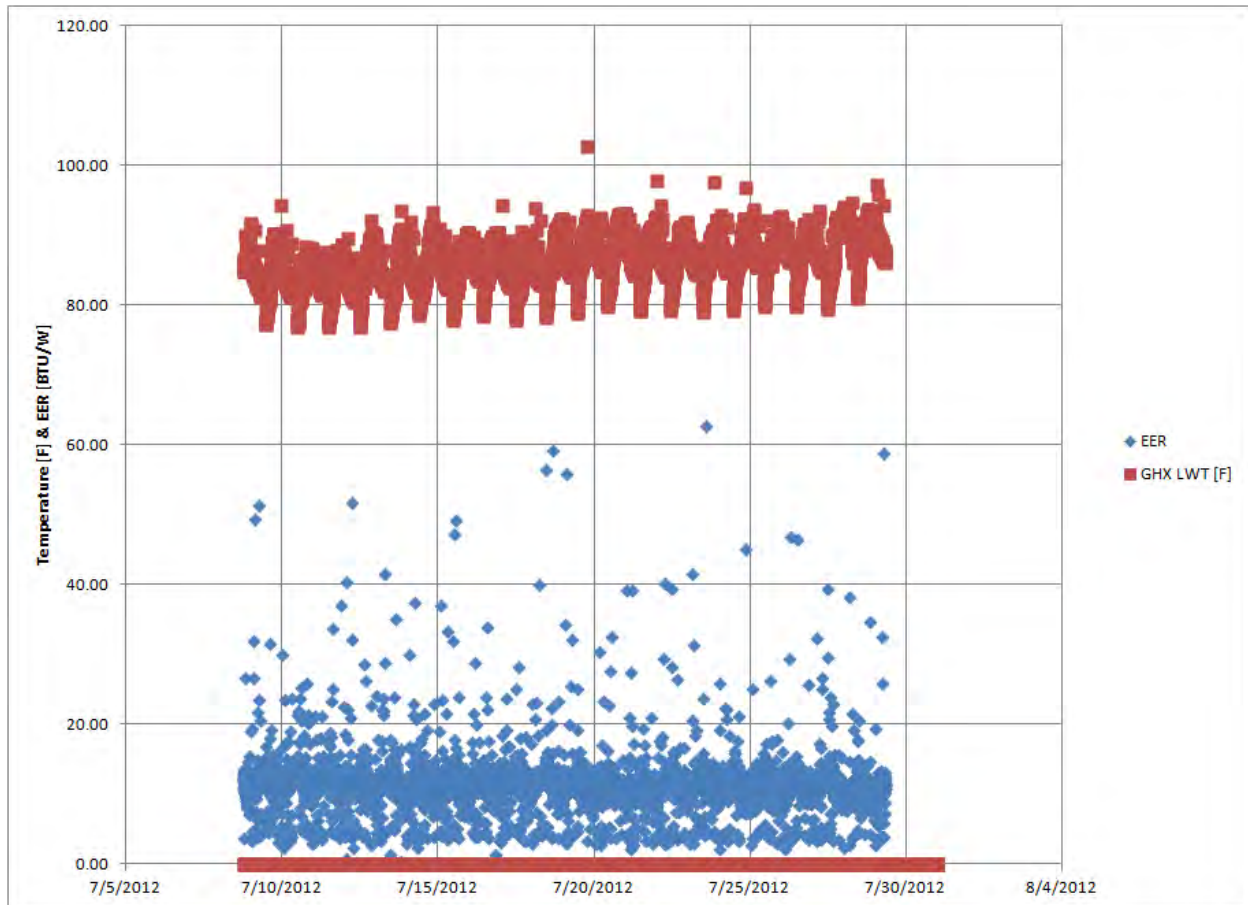


Figure B-5-1-3. Calculated system EER (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

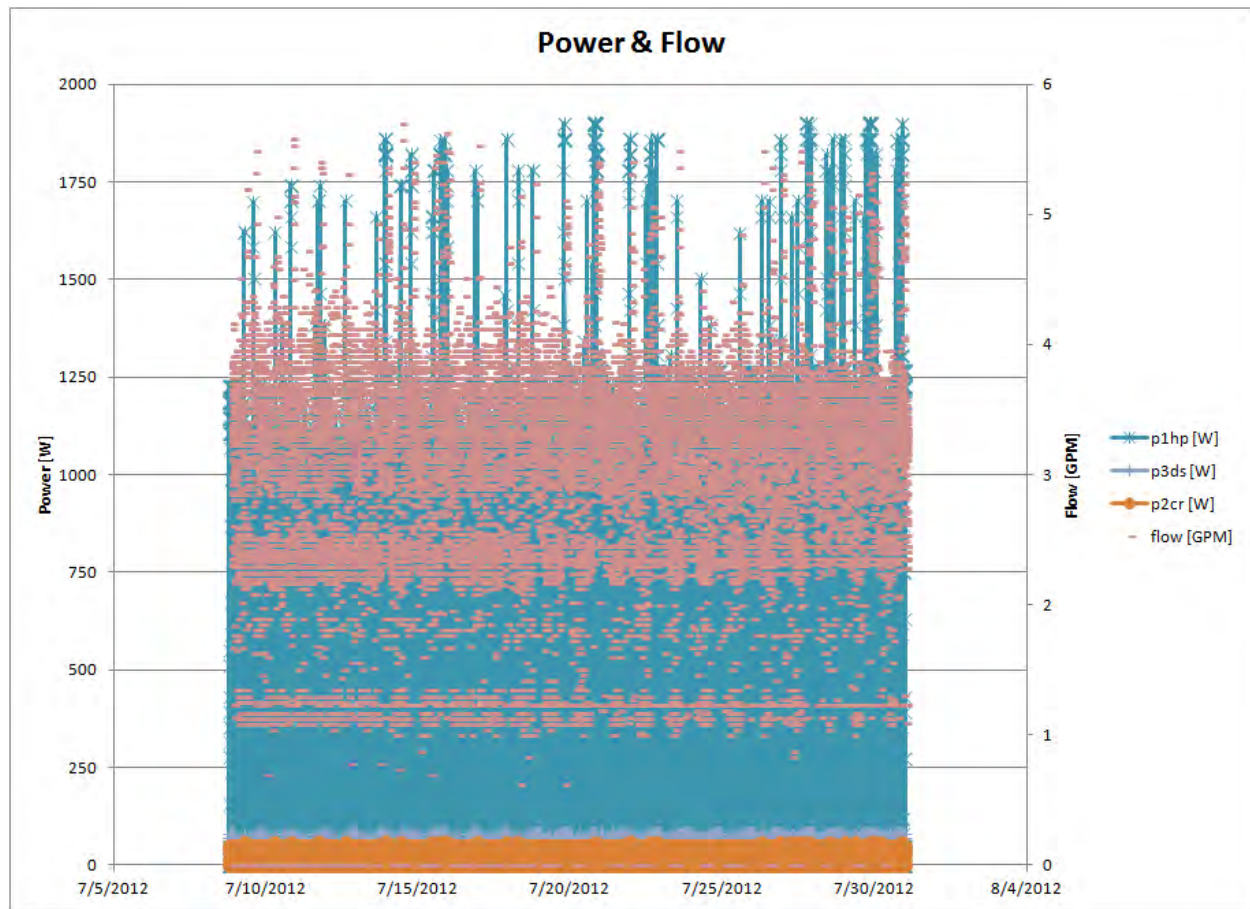


Figure B-5-3-1. Measured power and flow rate

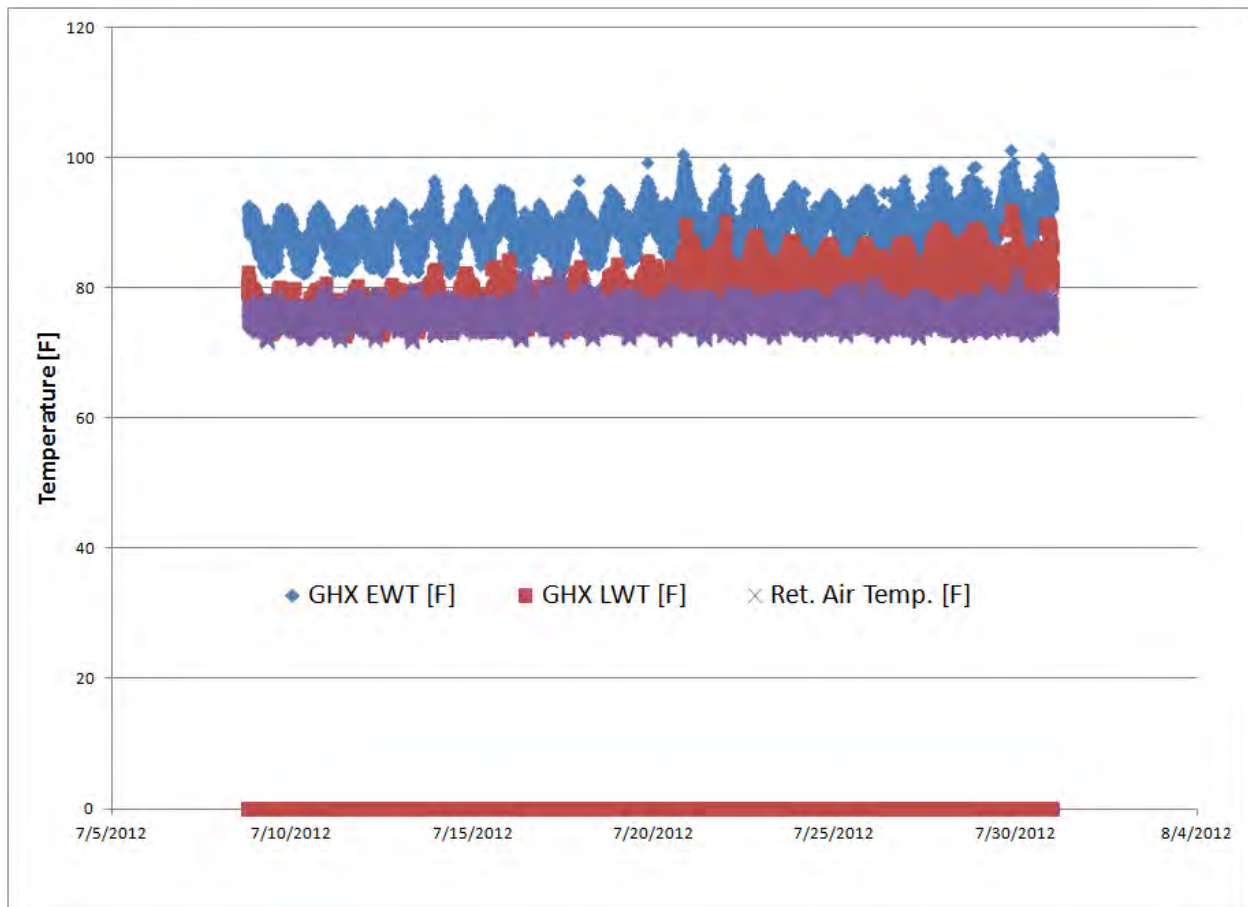


Figure B-5-3-2. Measured room and loop temperatures

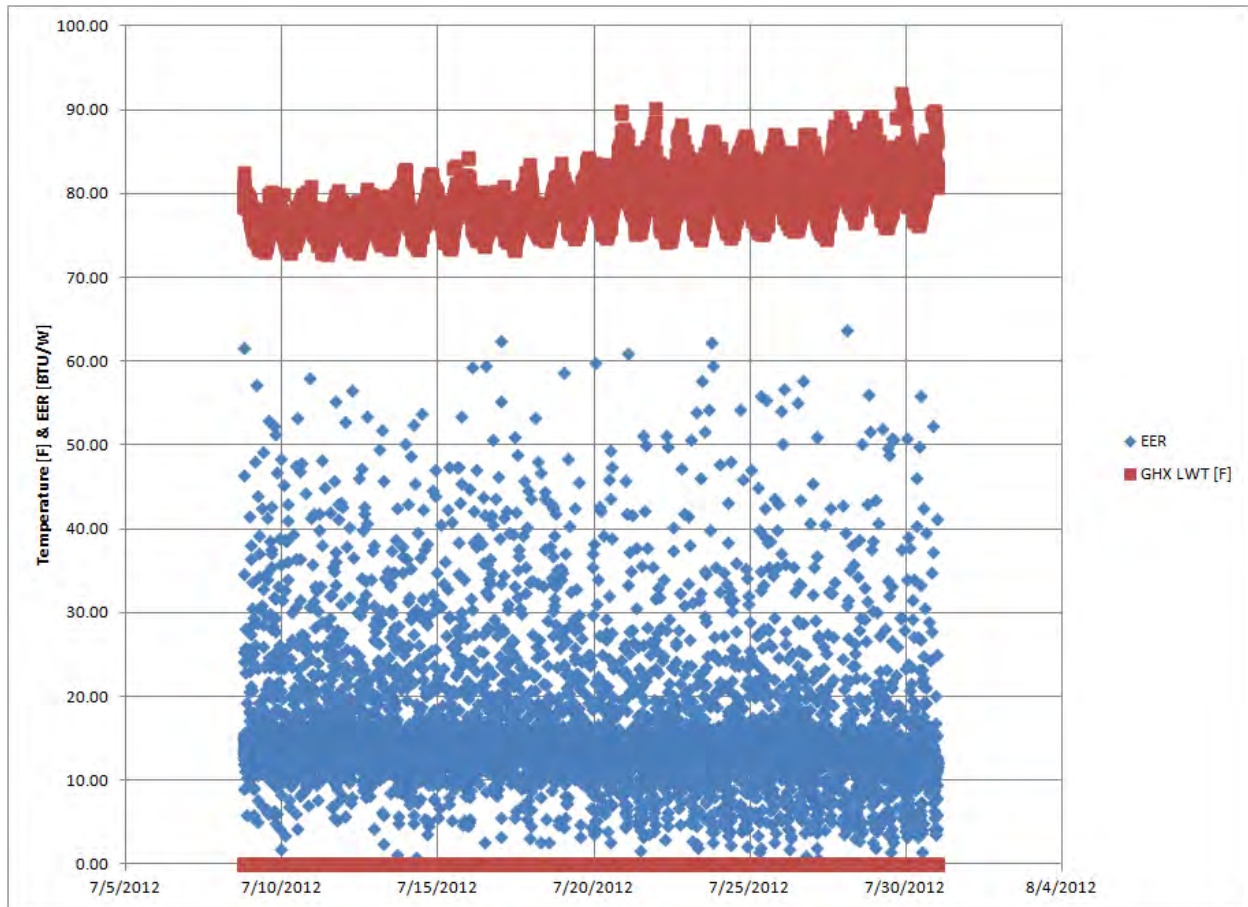


Figure B-5-3-3. Calculated system EER (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

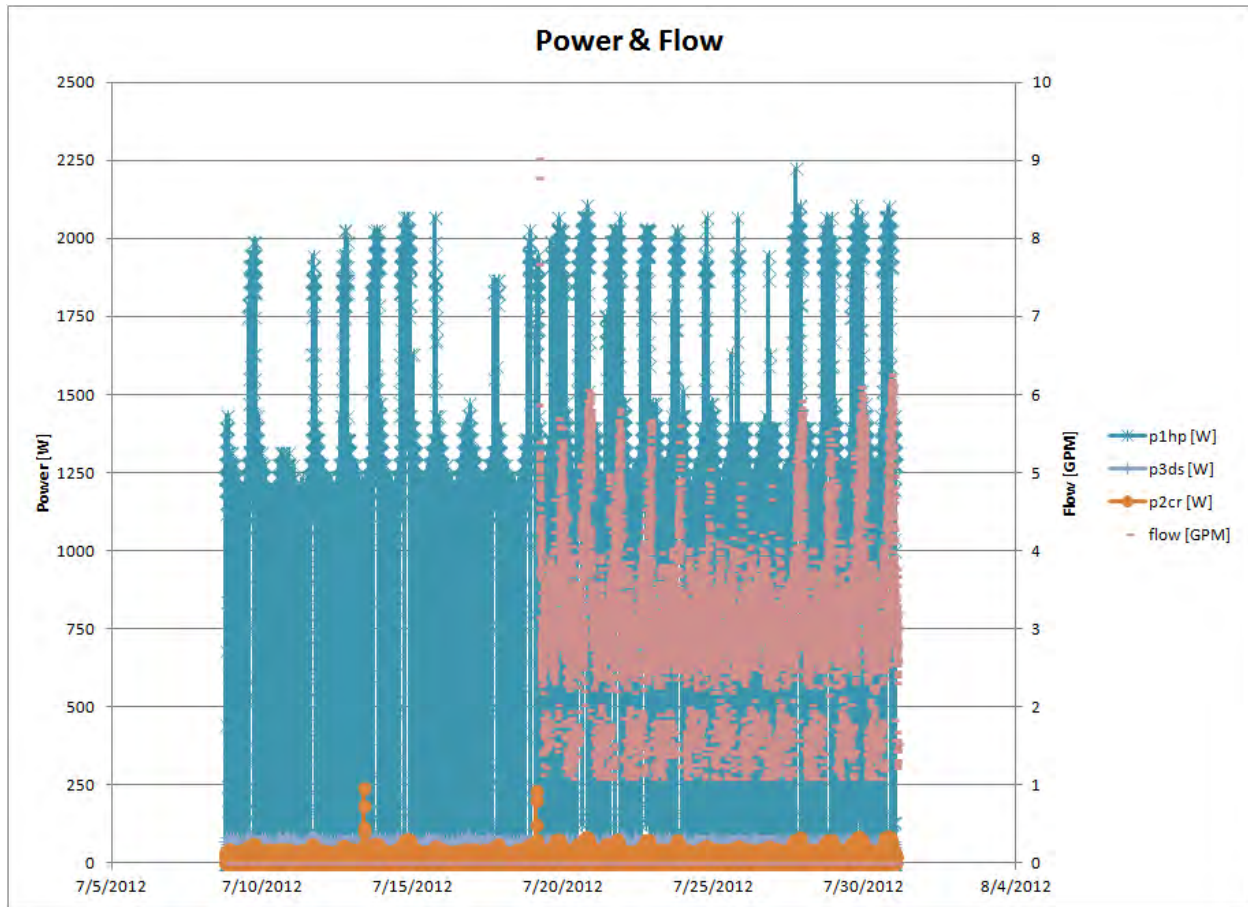


Figure B-5-4-1. Measured power and flow rate

Flow rate data was missing in the first 20 days of this month.

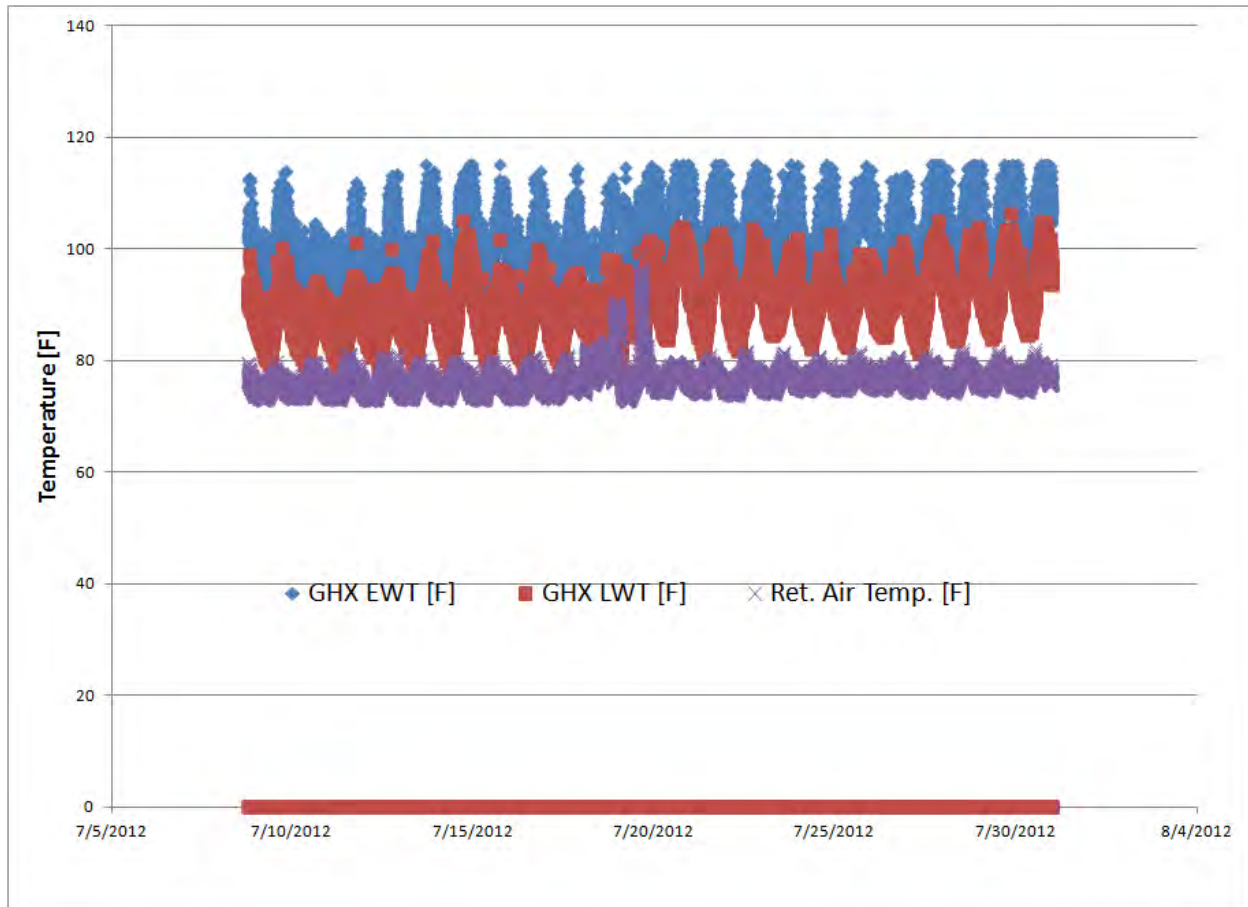


Figure B-5-4-2. Measured room and loop temperatures

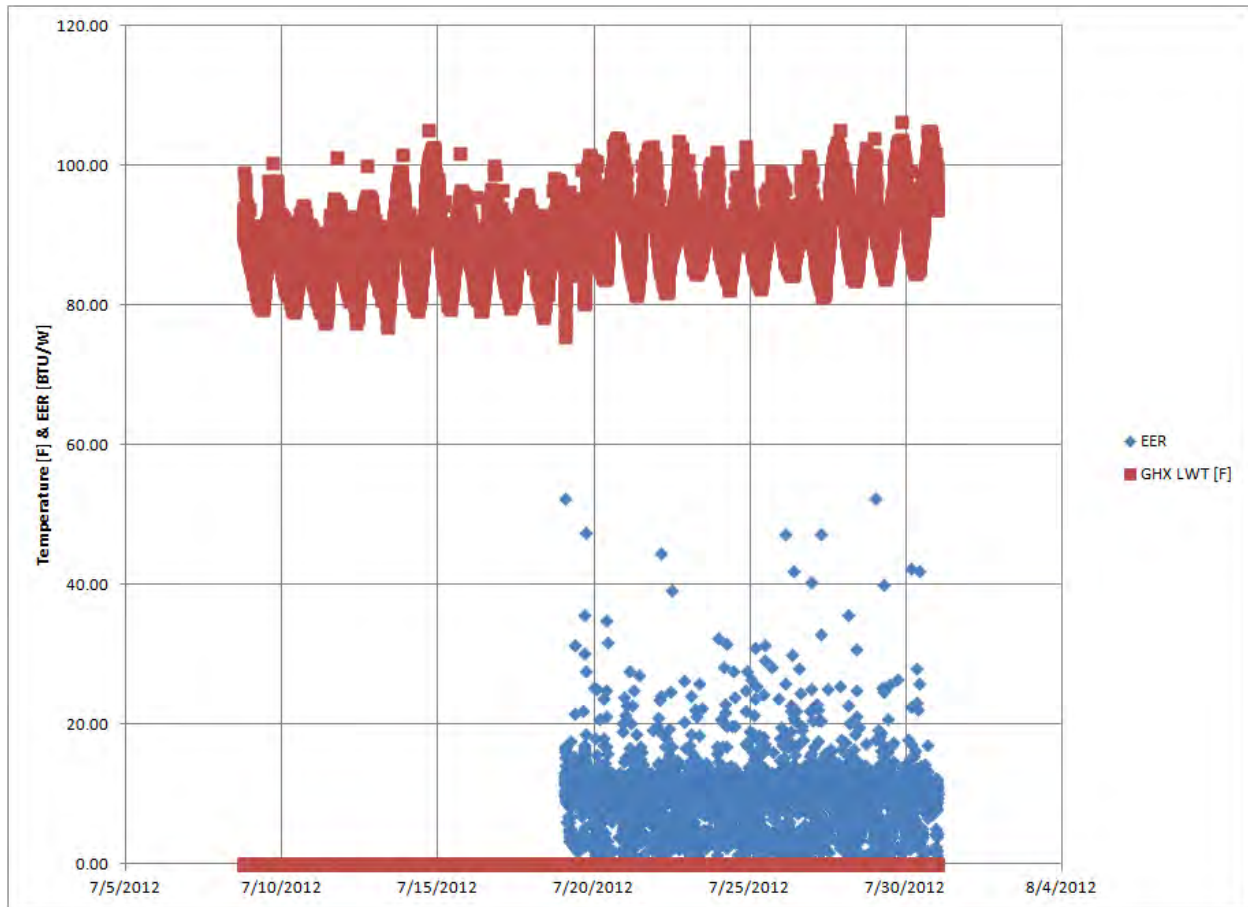


Figure B-5-4-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

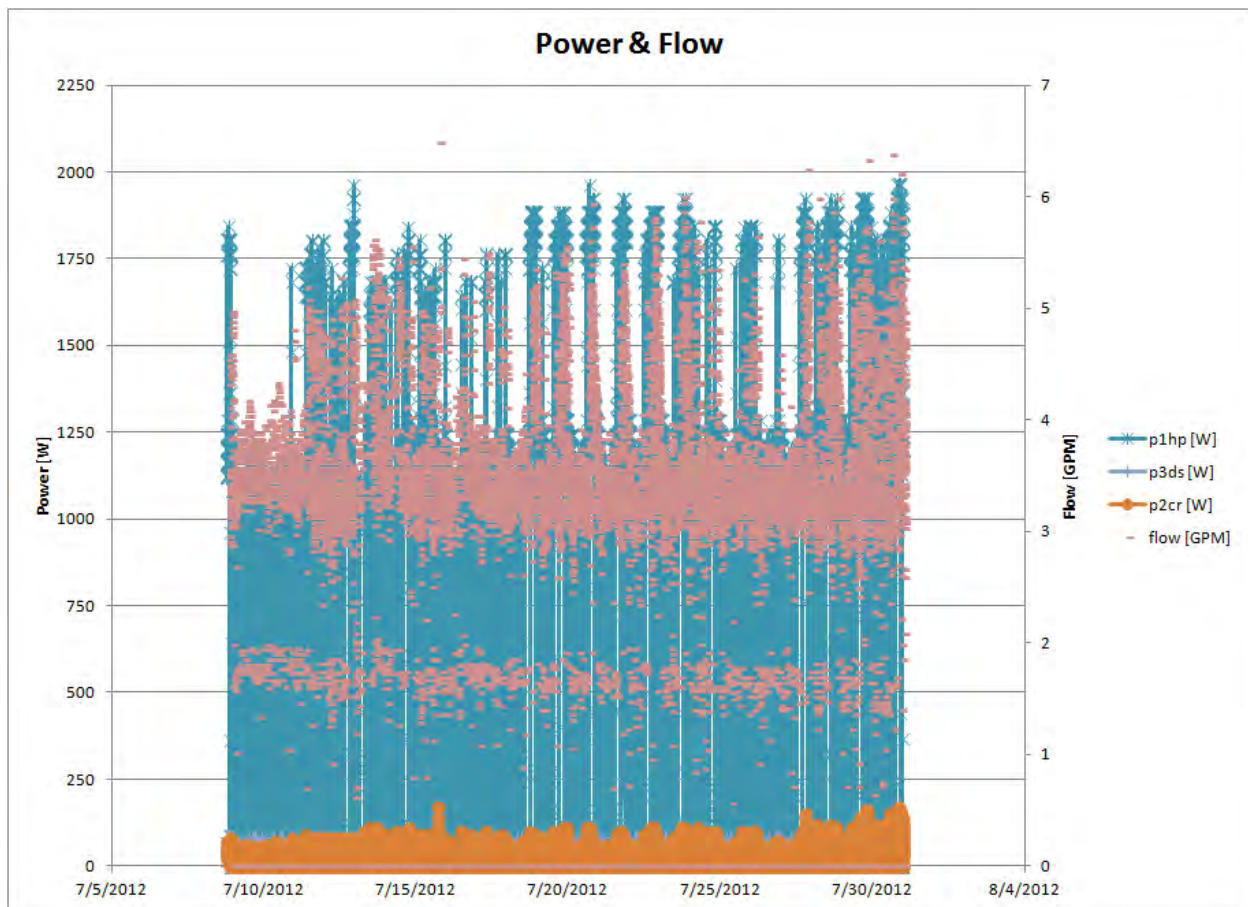


Figure B-5-5-1. Measured power and flow rate

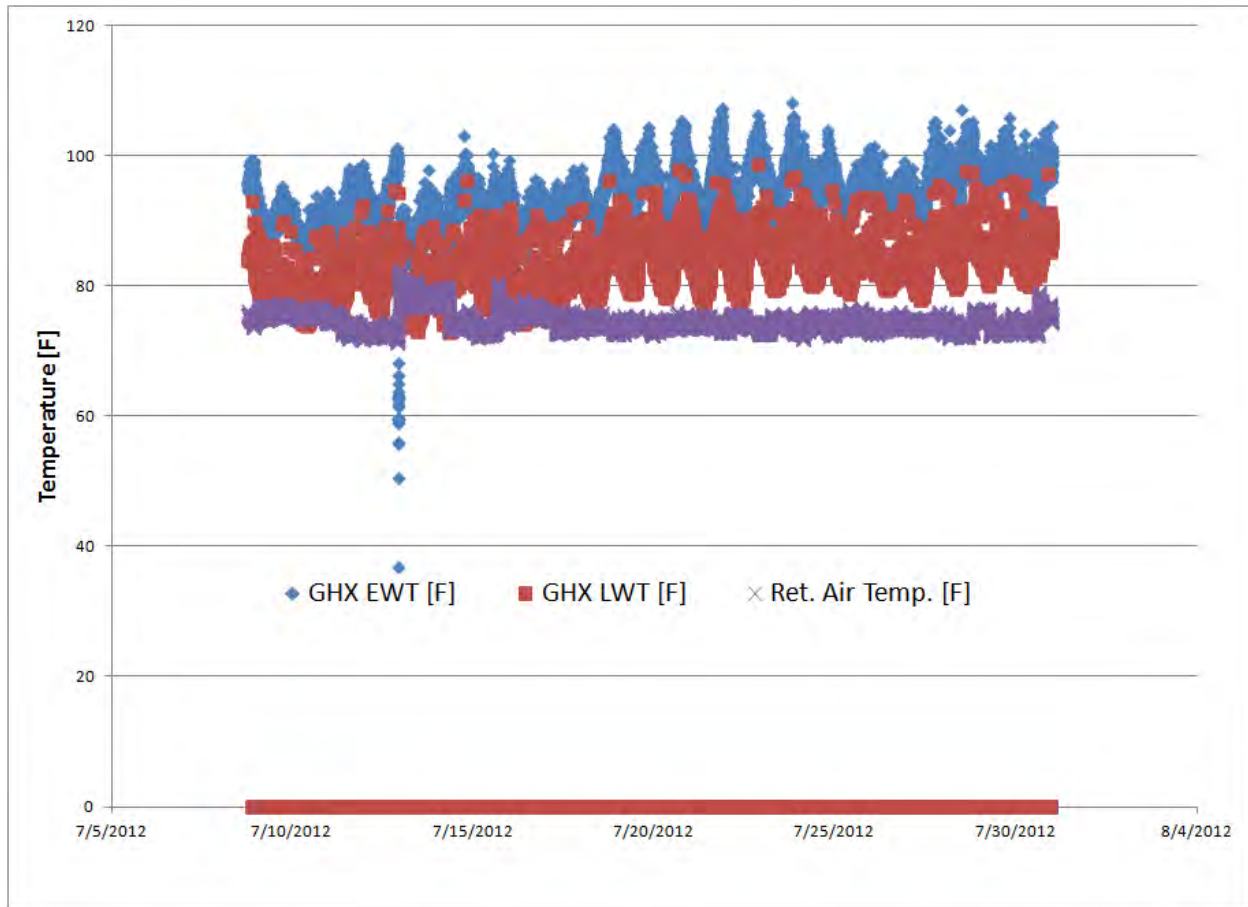


Figure B-5-5-2. Measured room and loop temperatures

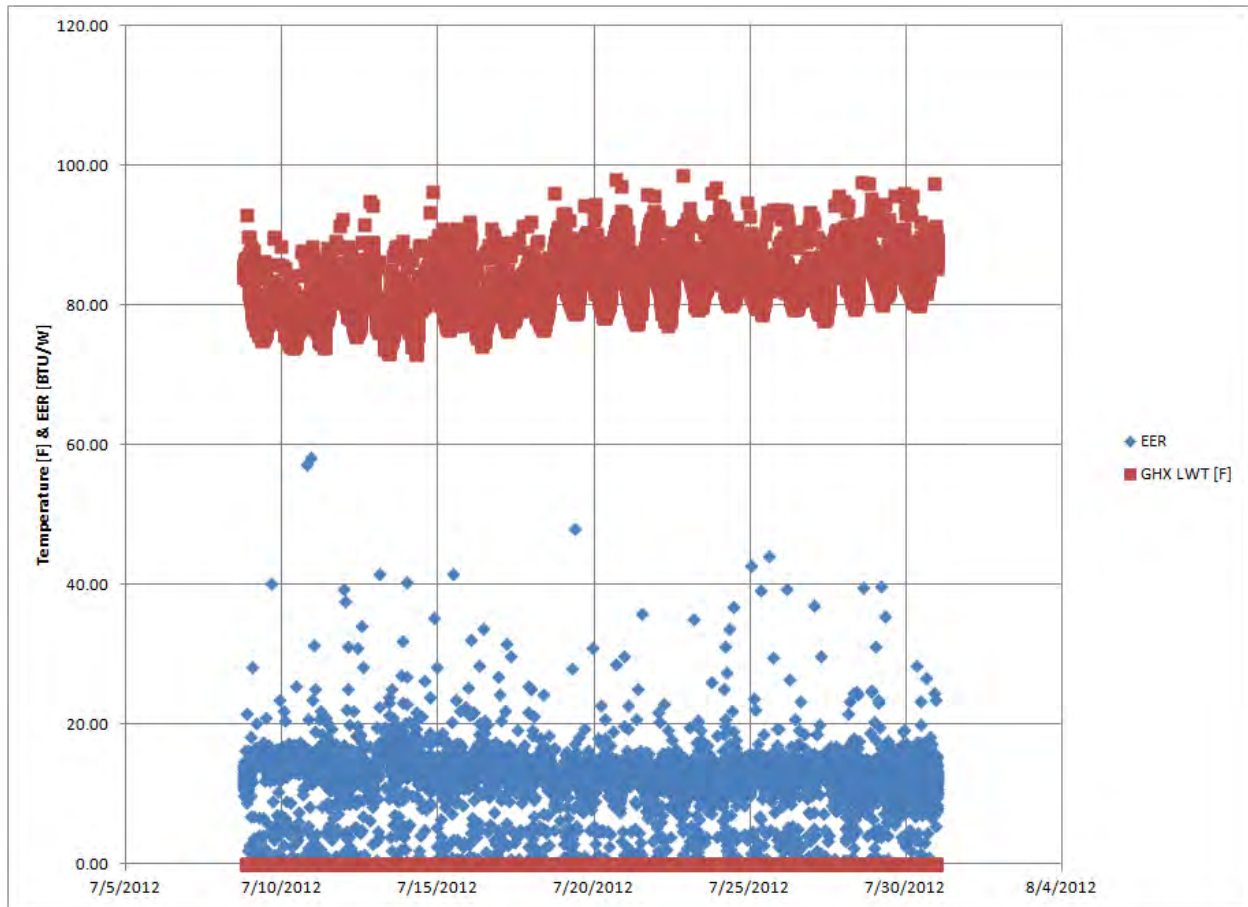


Figure B-5-5-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

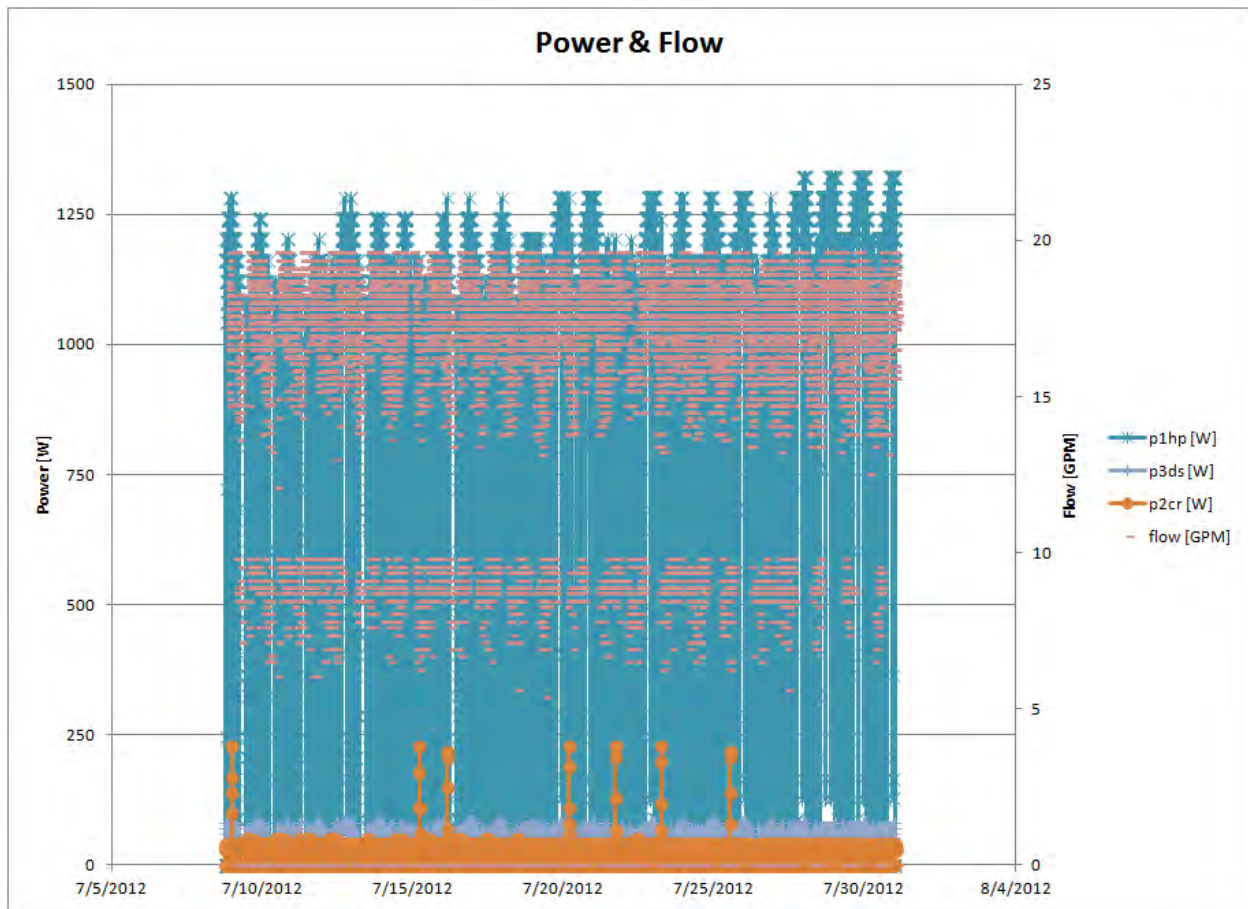


Figure B-5-6-1. Measured power and flow rate

Average flow rate is 16.9 GPM (excluding all the zero flow rate data). The high flow rate measurements are not valid since the cooling/heating capacity calculated with the measured flow rate is more than double the nominal capacity of the 2 ton heat pump unit.

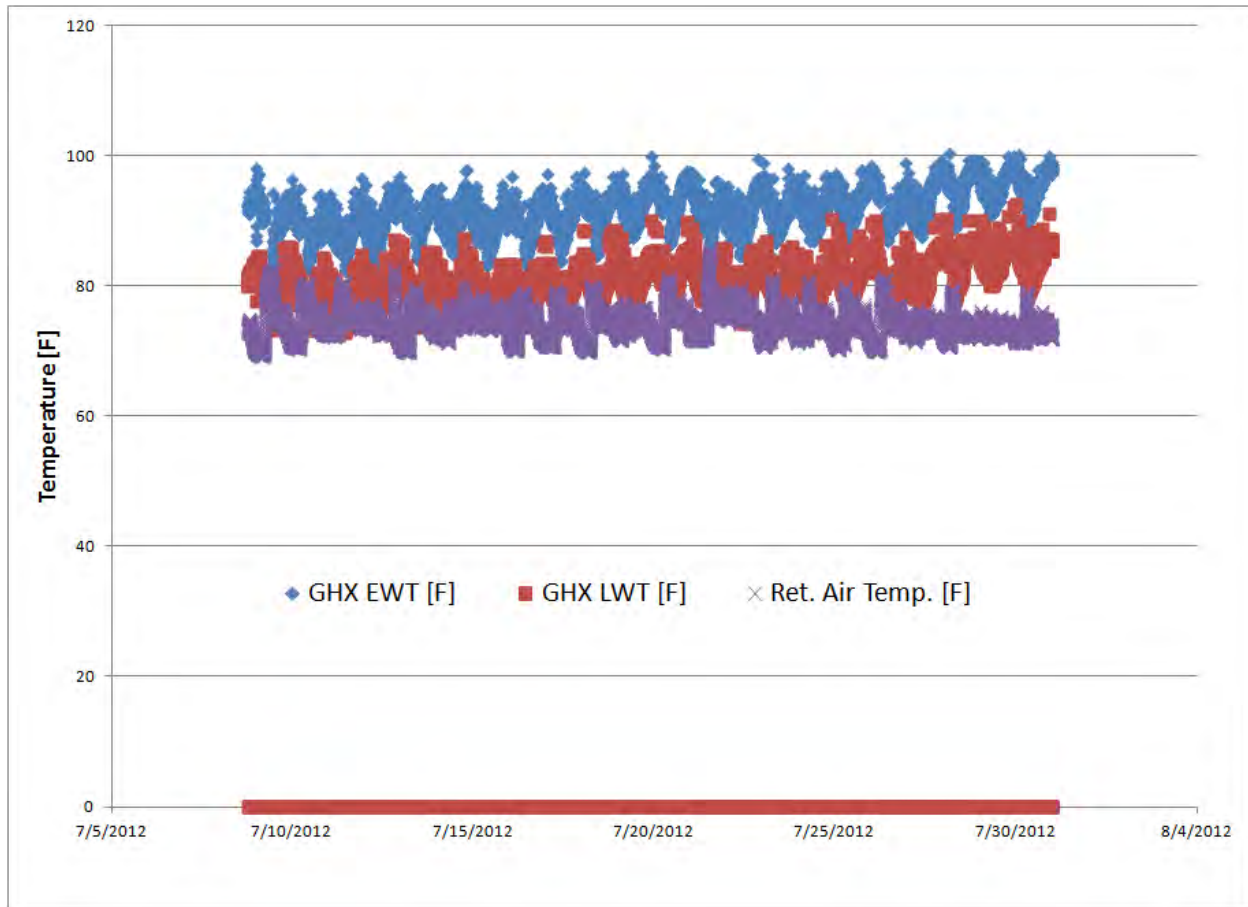


Figure B-5-6-2. Measured room and loop temperatures

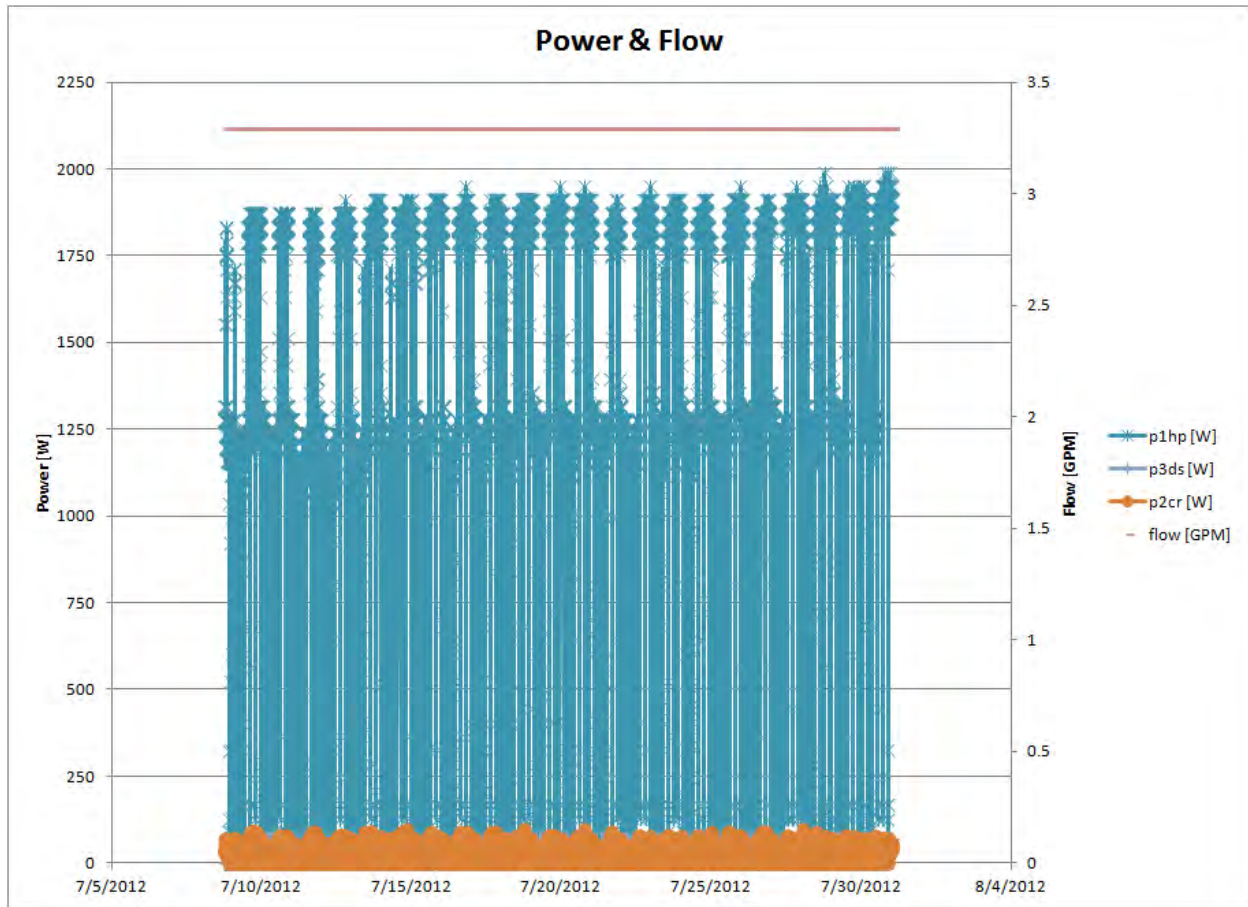


Figure B-5-7-1. Measured power and flow rate

No valid flow rate data in this month.

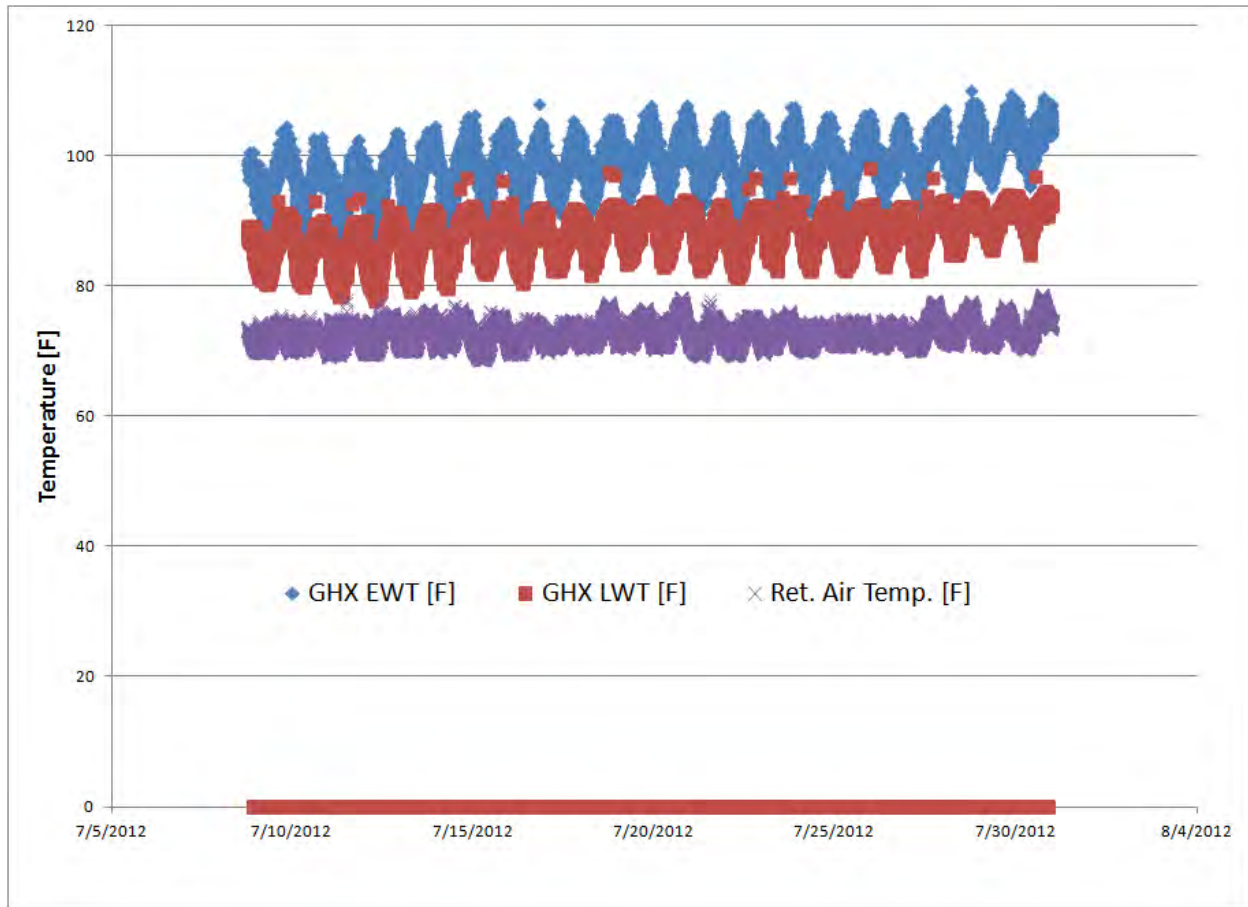


Figure B-5-7-2. Measured room and loop temperatures

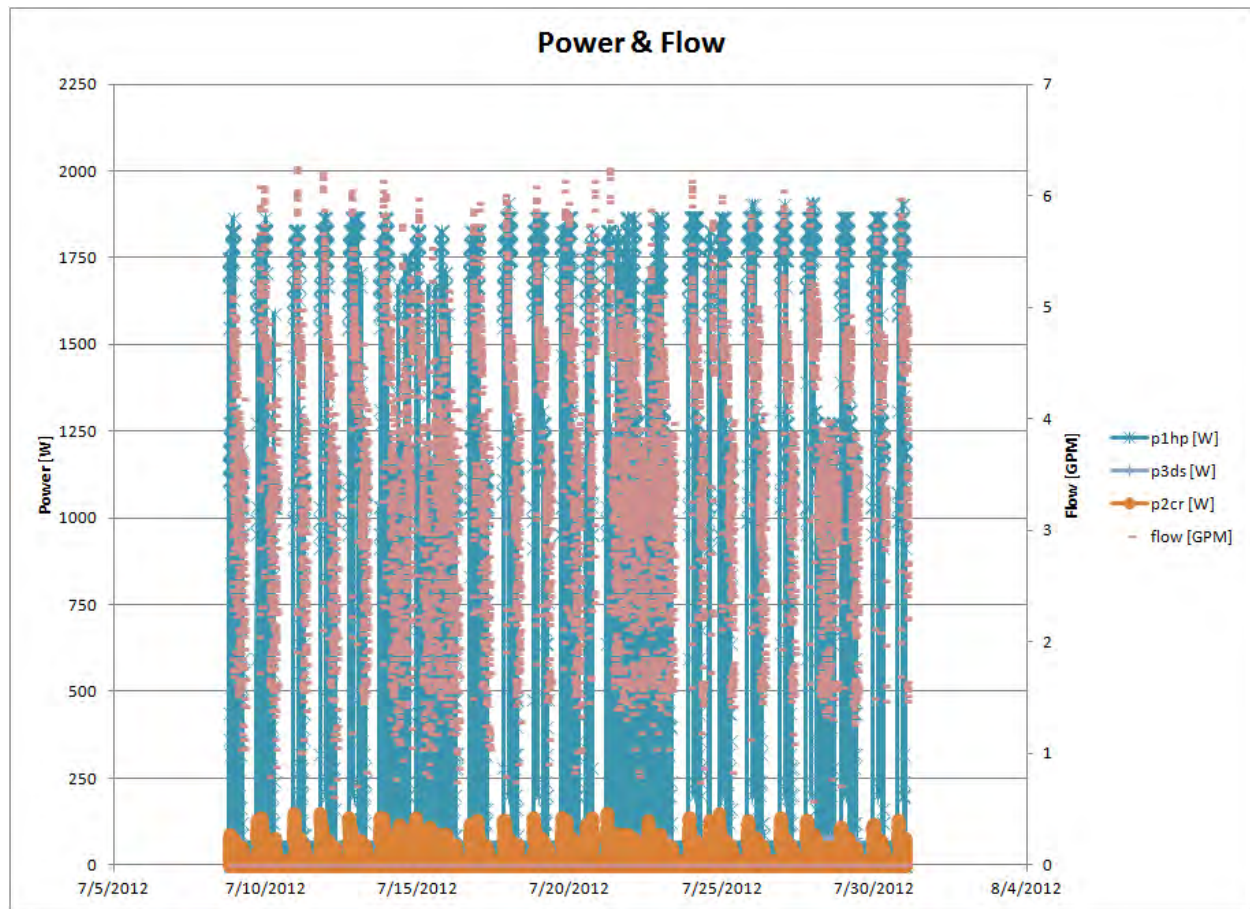


Figure B-5-8-1. Measured power and flow rate

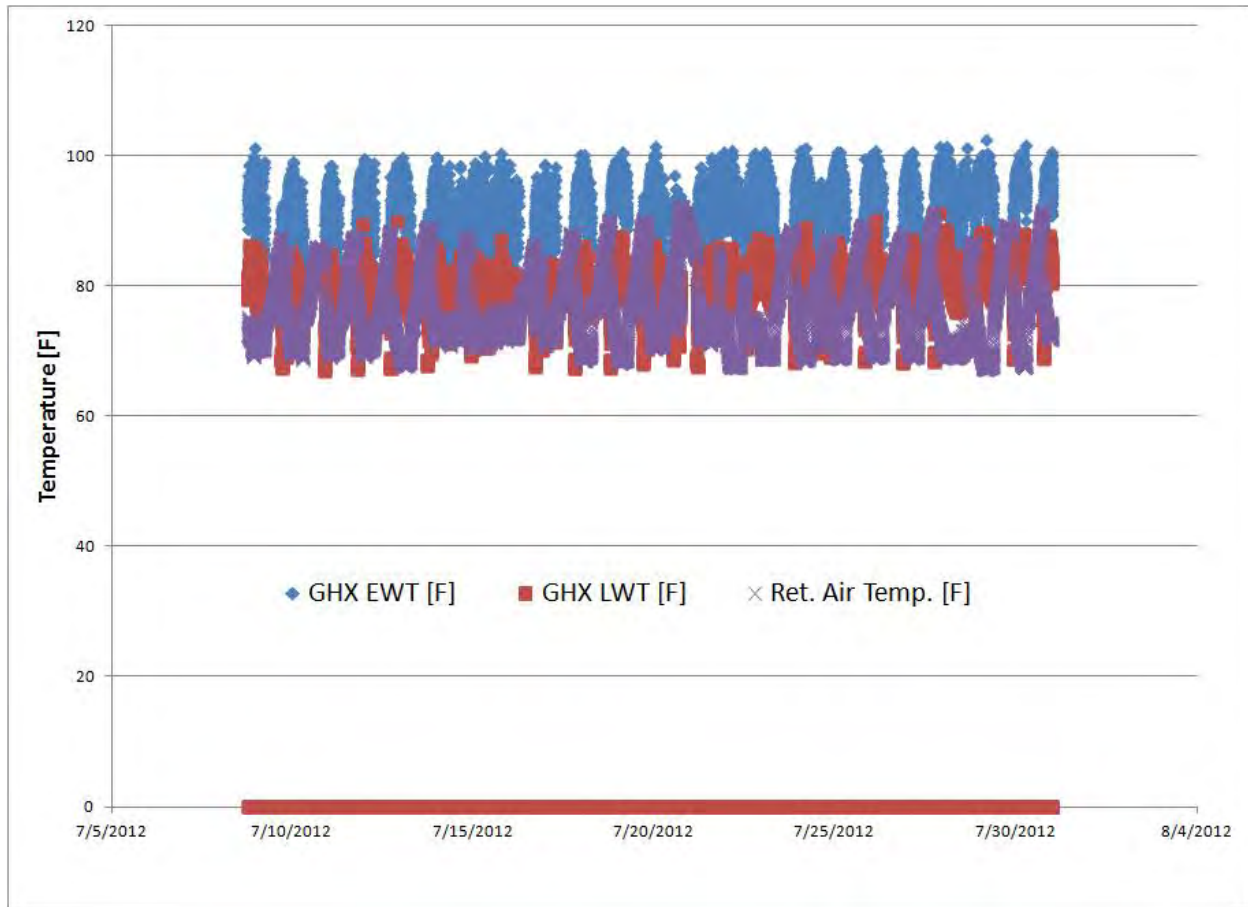


Figure B-5-8-2. Measured room and loop temperatures

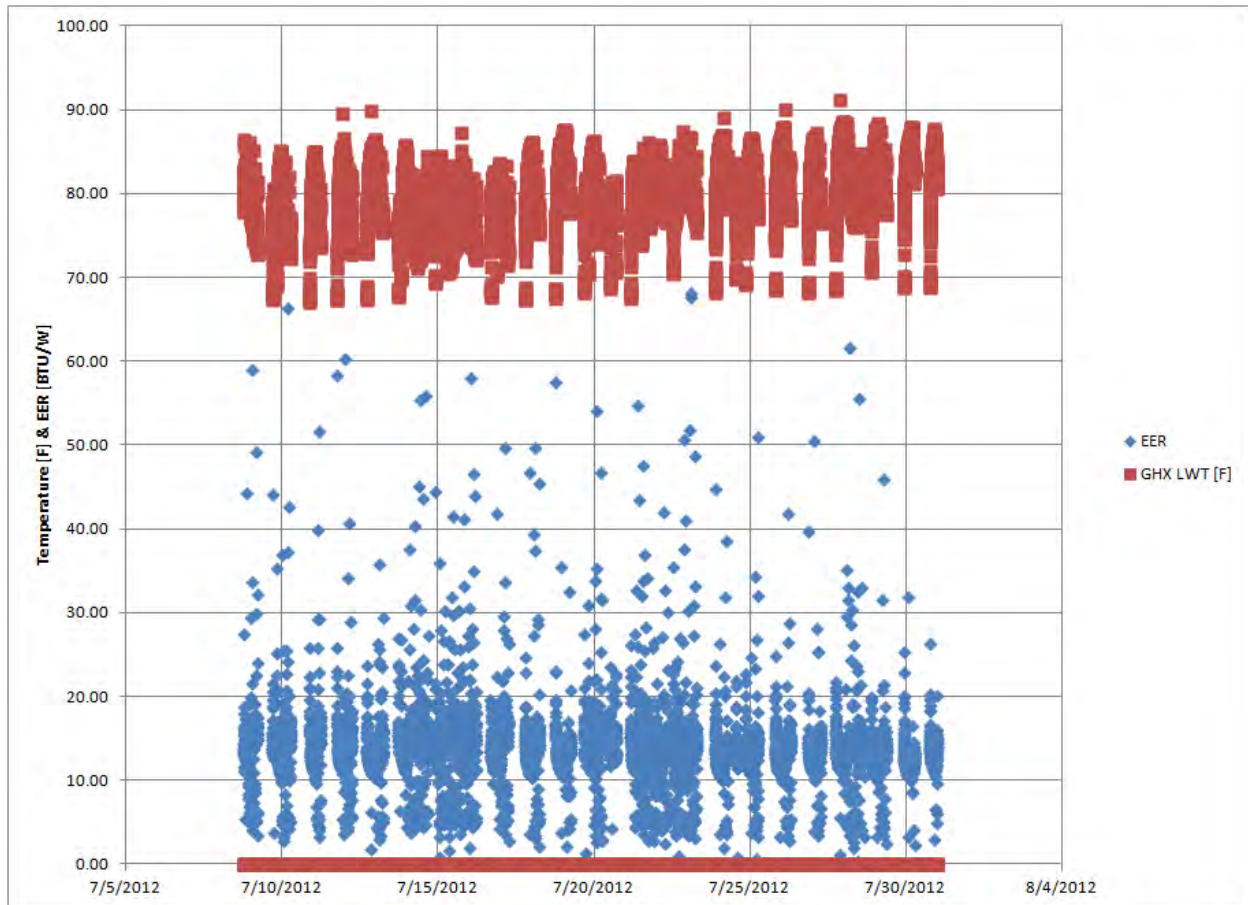


Figure B-5-8-3. Calculated system EER (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

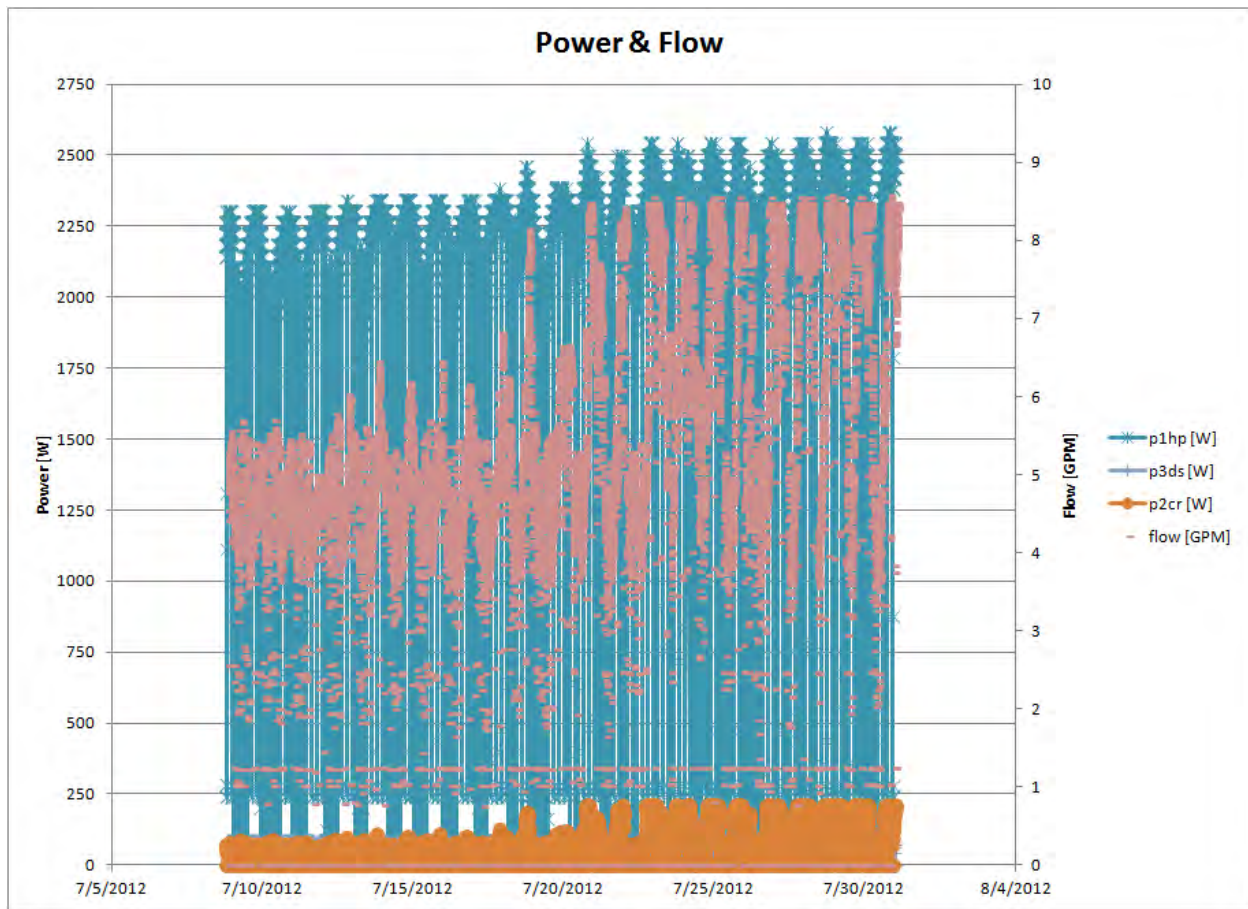


Figure B-5-9-1. Measured power and flow rate

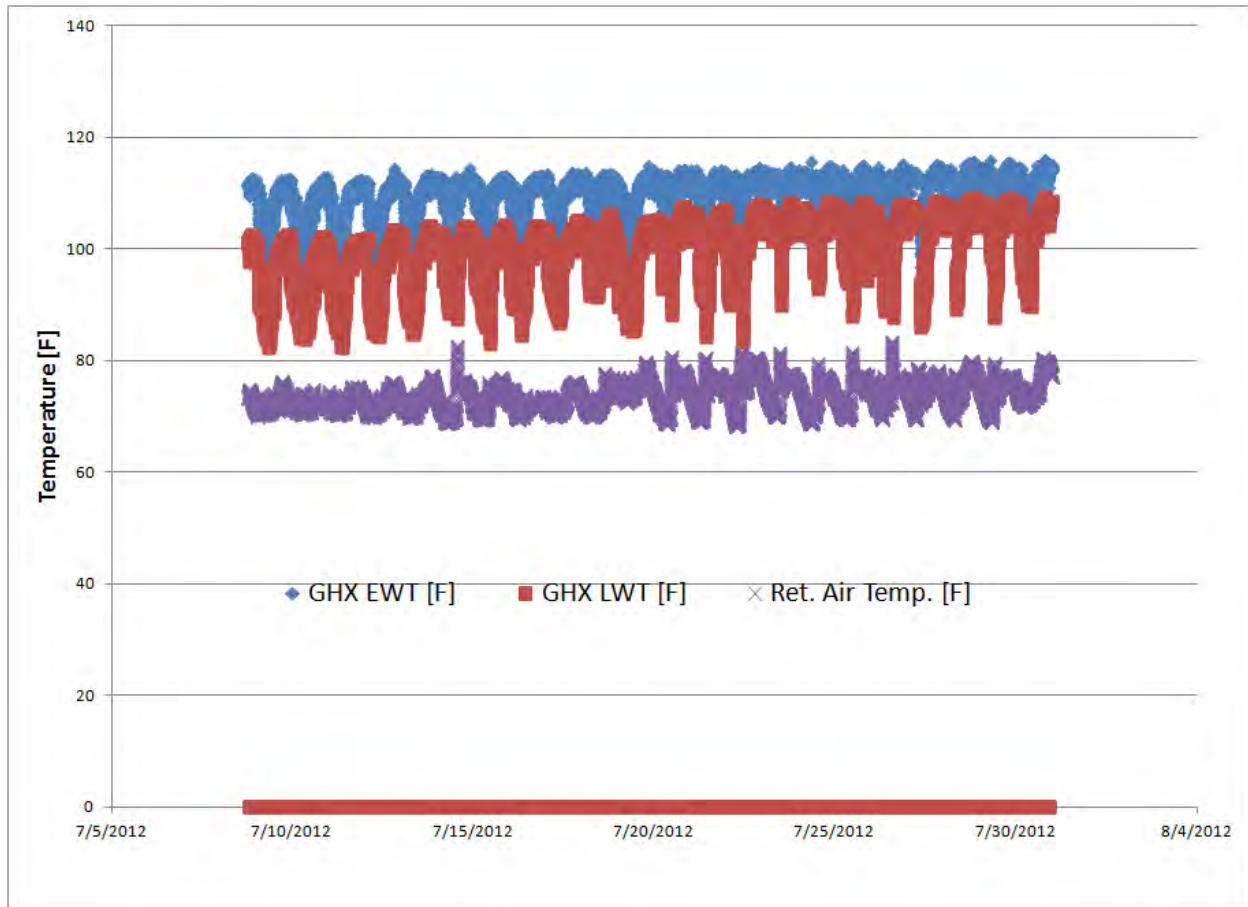


Figure B-5-9-2. Measured room and loop temperatures

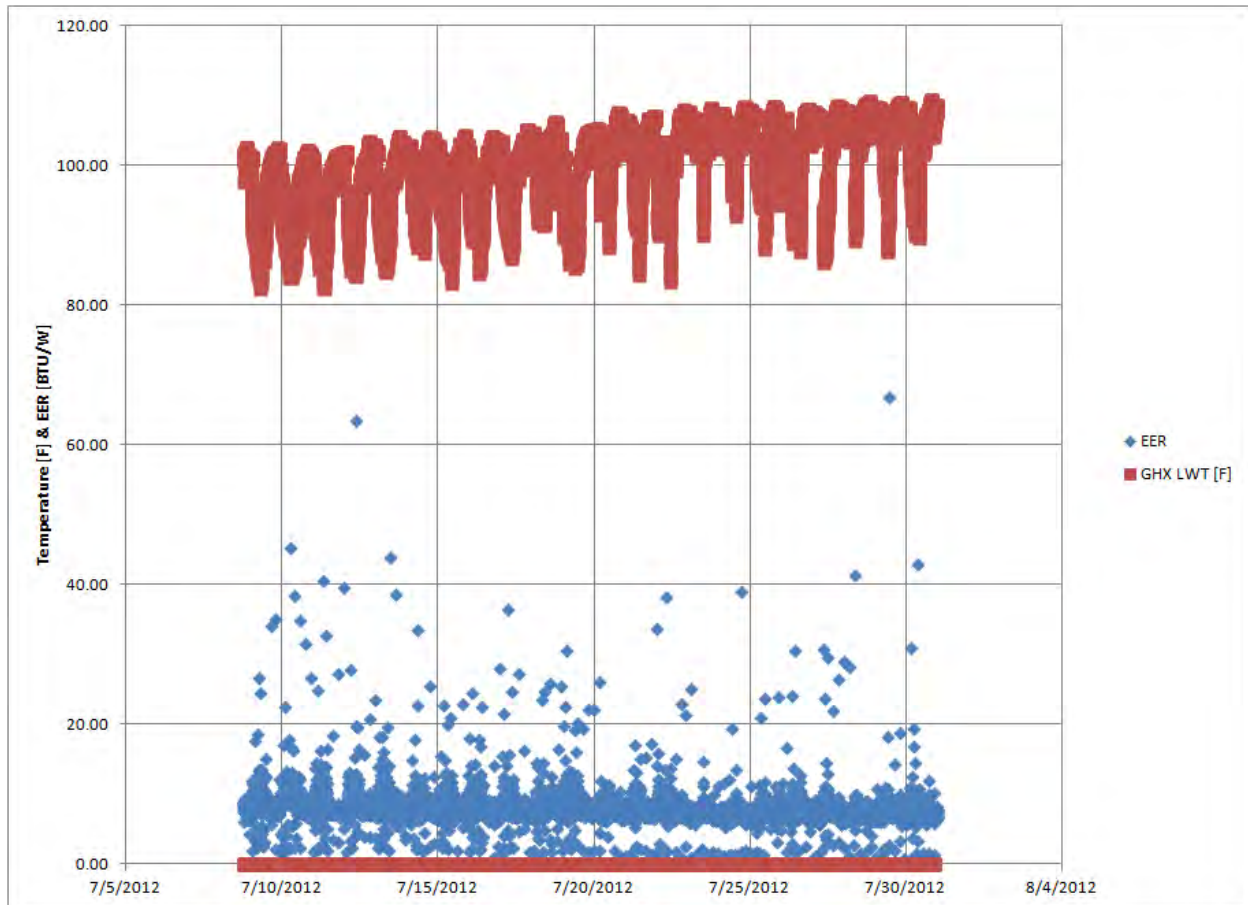


Figure B-5-9-3. Calculated system EER (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 10 (8528)

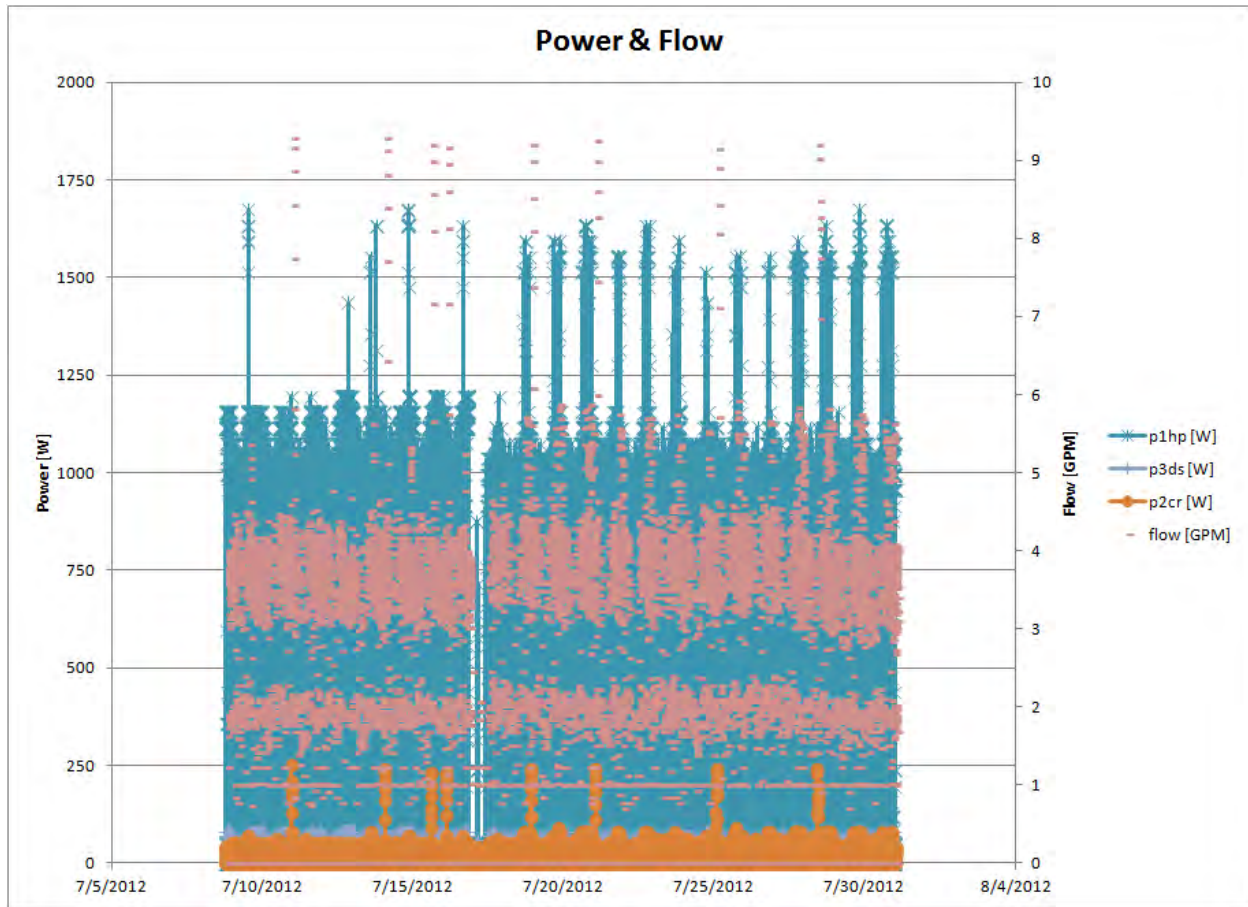


Figure B-5-10-1. Measured power and flow rate

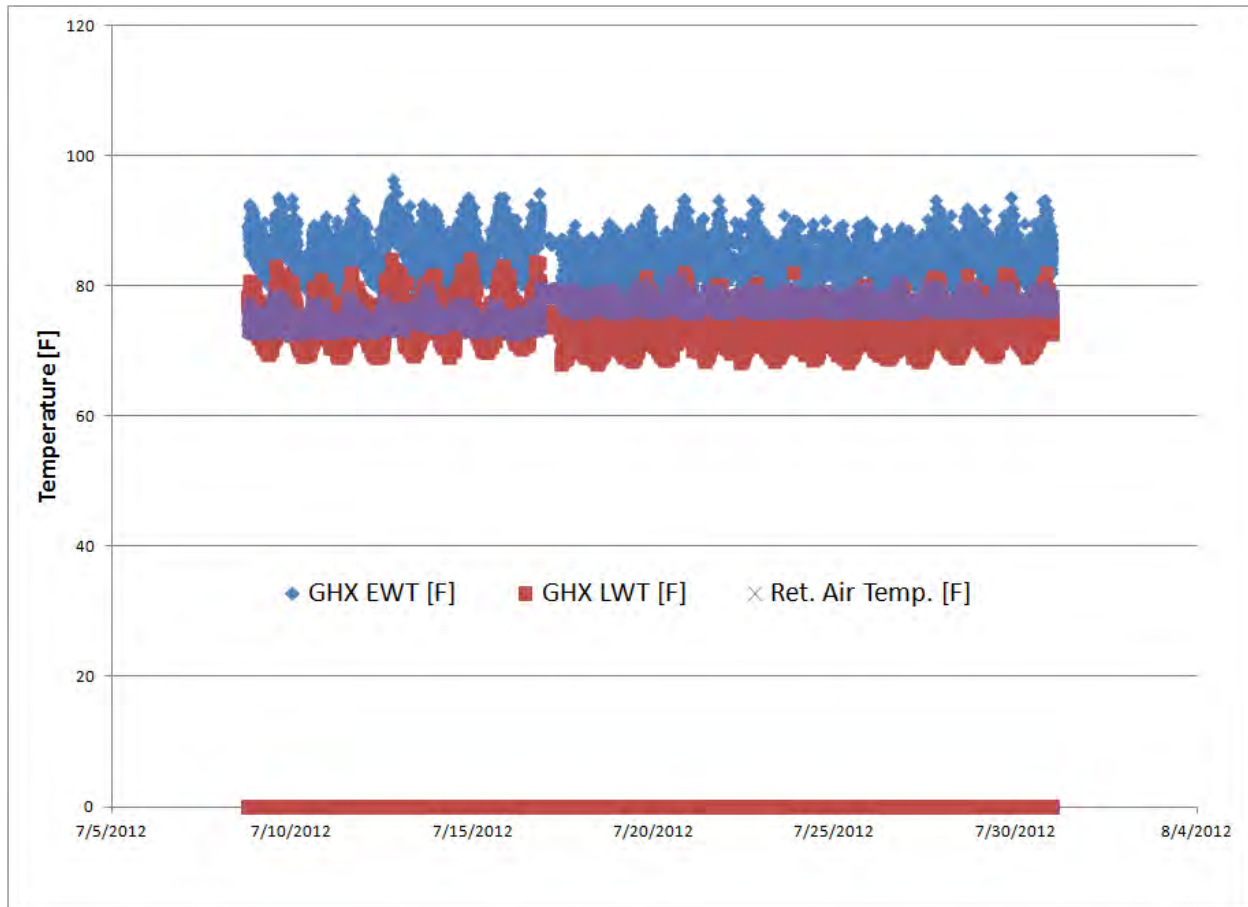


Figure B-5-10-2. Measured room and loop temperatures

Before 7/17, the room temperature set-point was at around 74°F and it was increased to 76°F from then on.

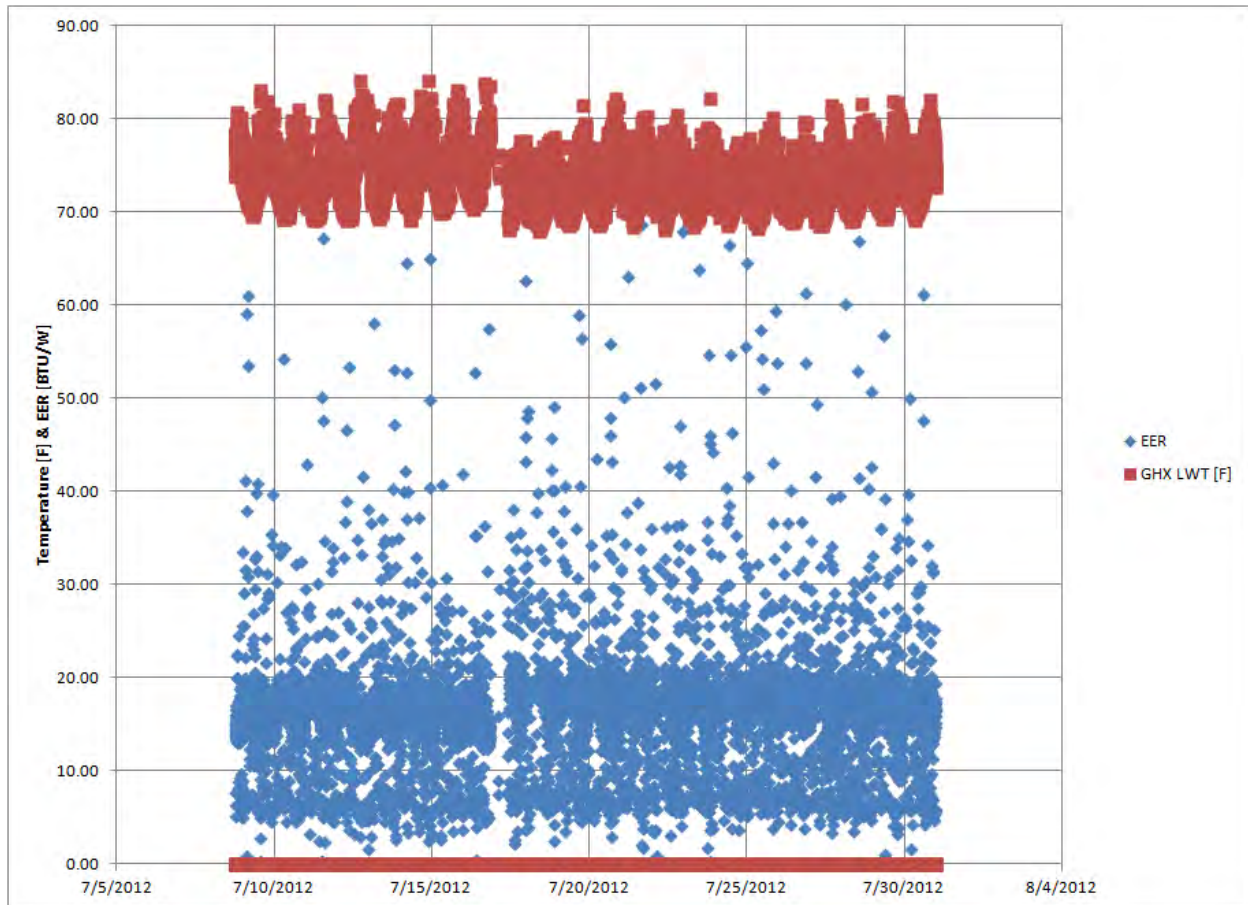


Figure B-5-10-3. Calculated system EER (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

B-6: AUGUST 2012

Unit 01 (925)

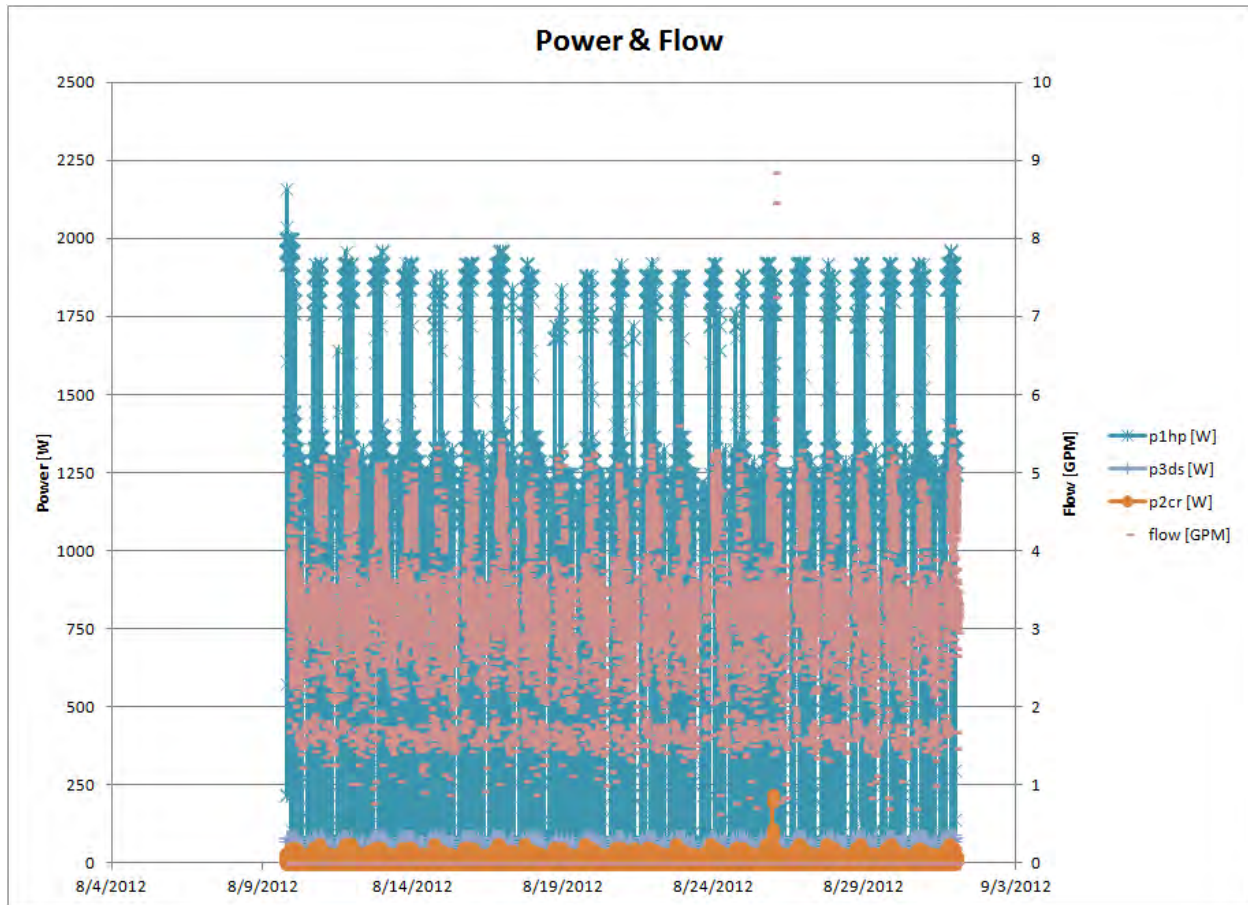


Figure B-6-1-1. Measured power and flow rate

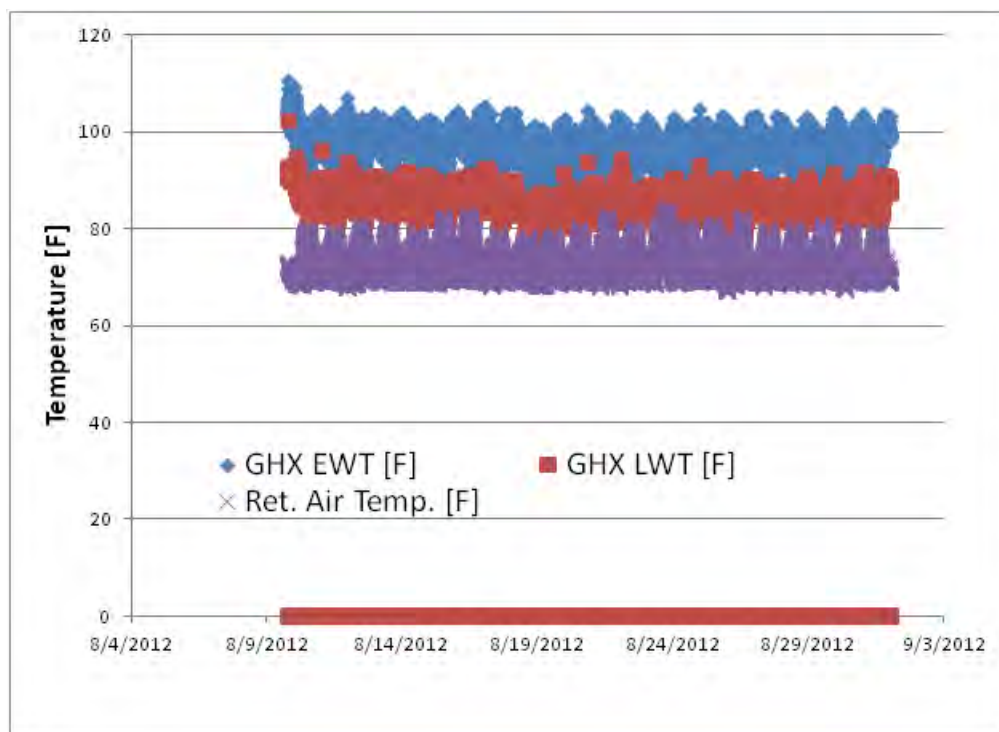


Figure B-6-1-2. Measured room and loop temperatures

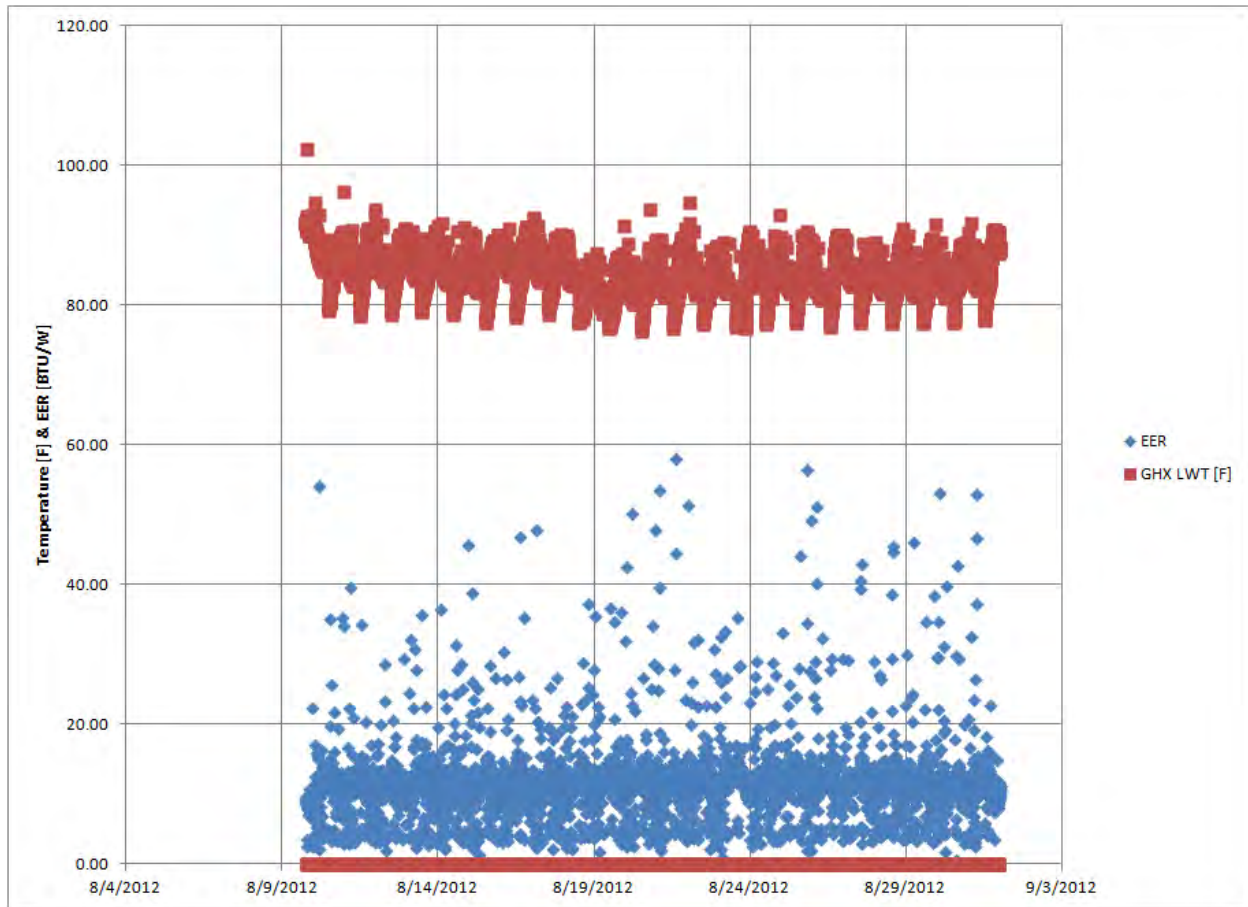


Figure B-6-1-3. Calculated system EER (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 03 (833)

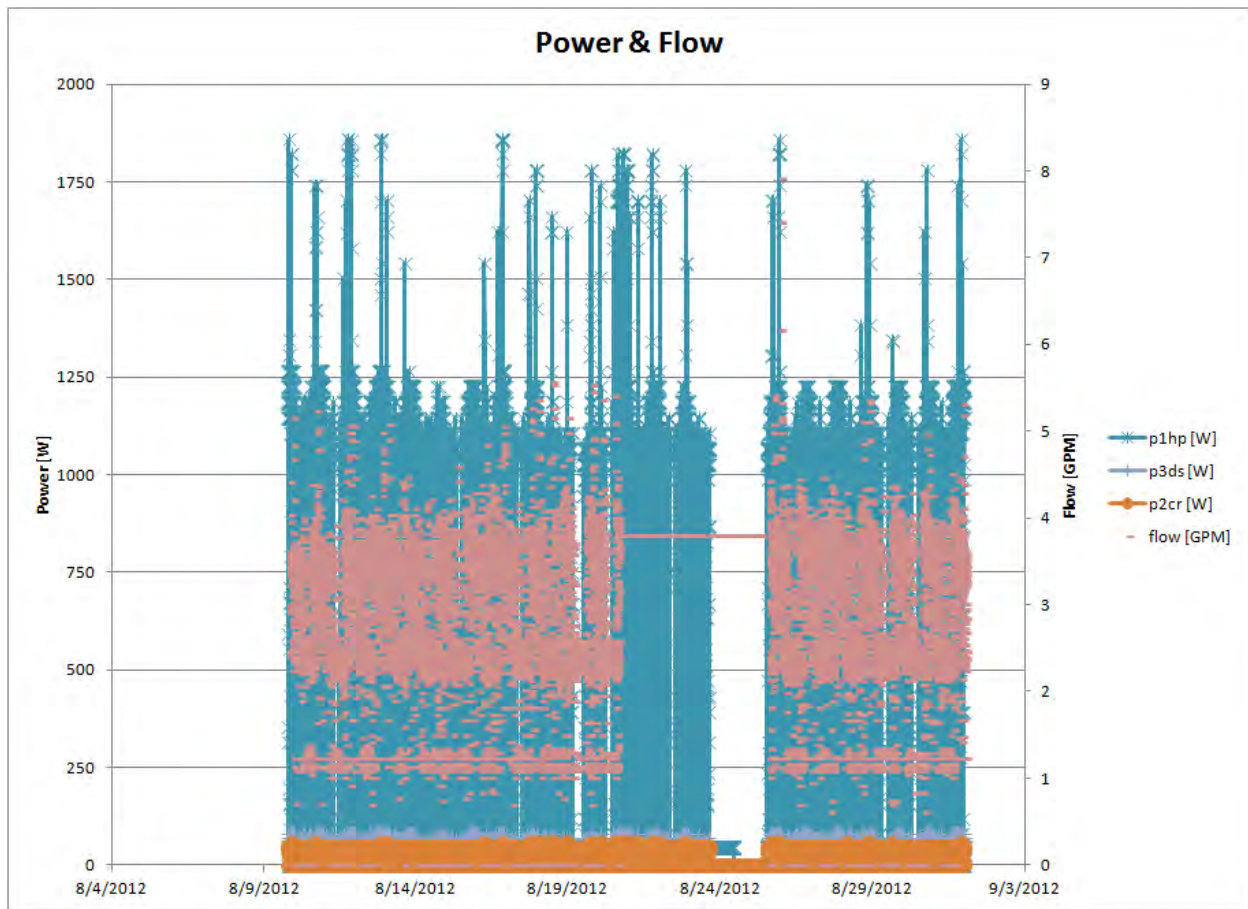


Figure B-6-3-1. Measured power and flow rate

Flow data is invalid from 8/20 through 8/25. Electric power data is missing (or the GSHP is turned off) from 8/24 through 8/25.

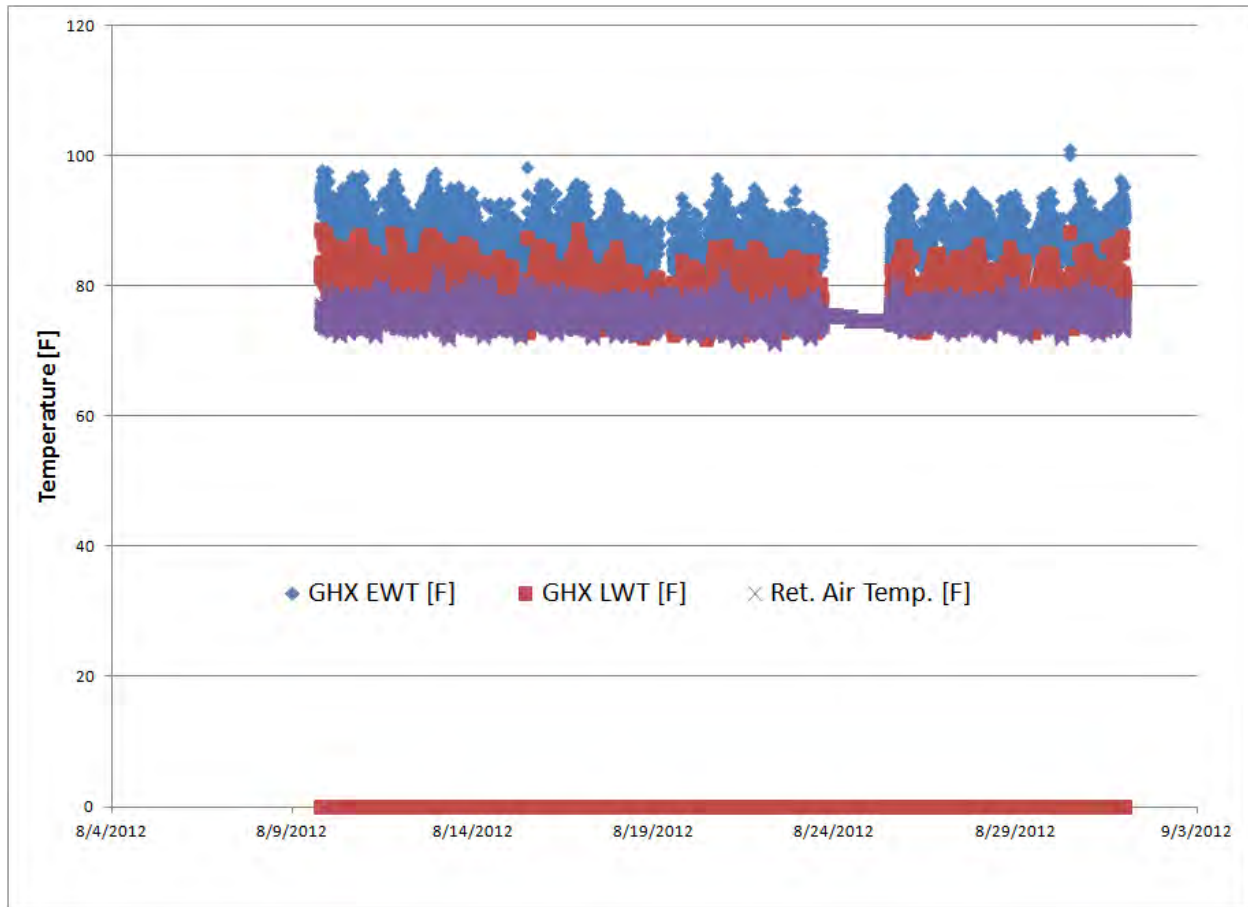


Figure B-6-3-2. Measured room and loop temperatures

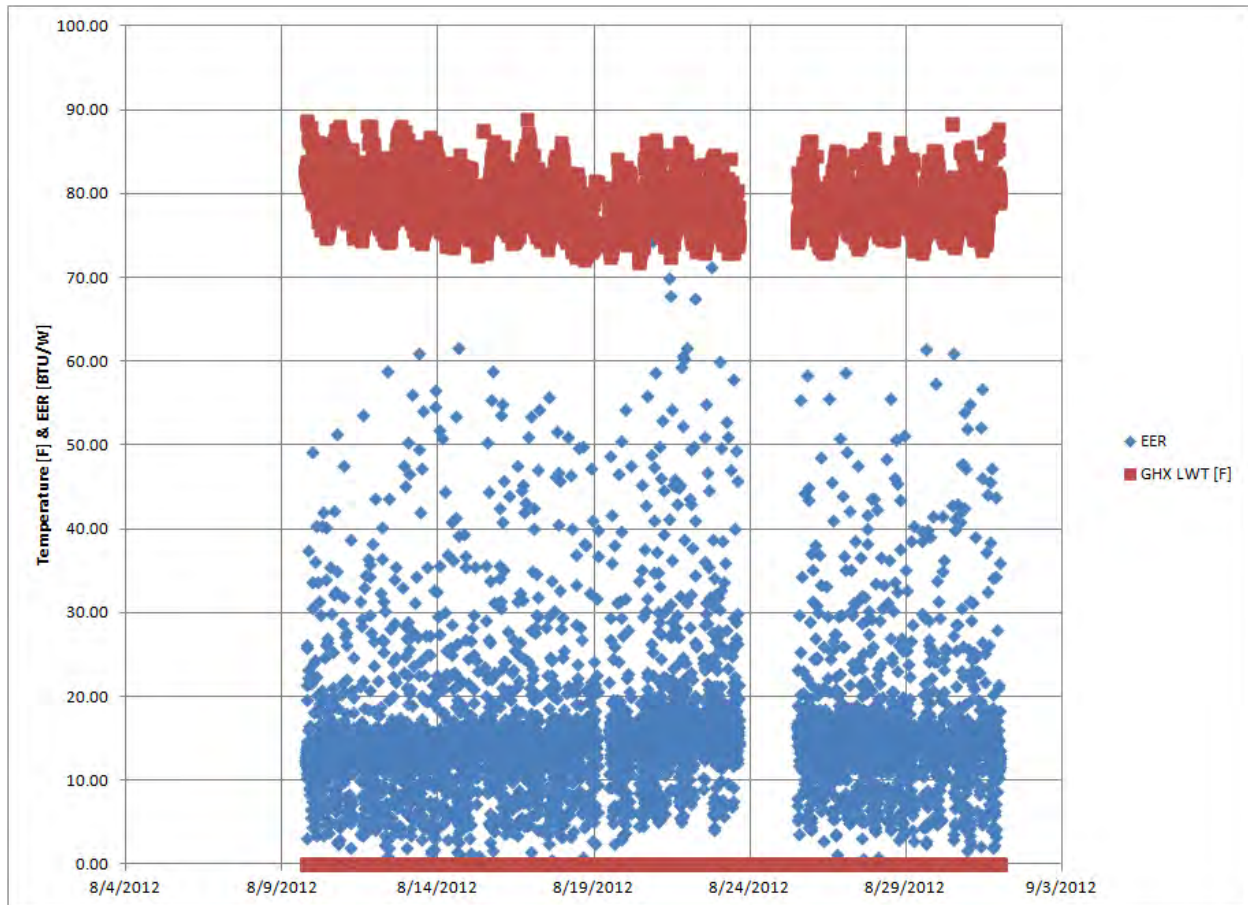


Figure B-6-3-3. Calculated system EER (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 04 (932)

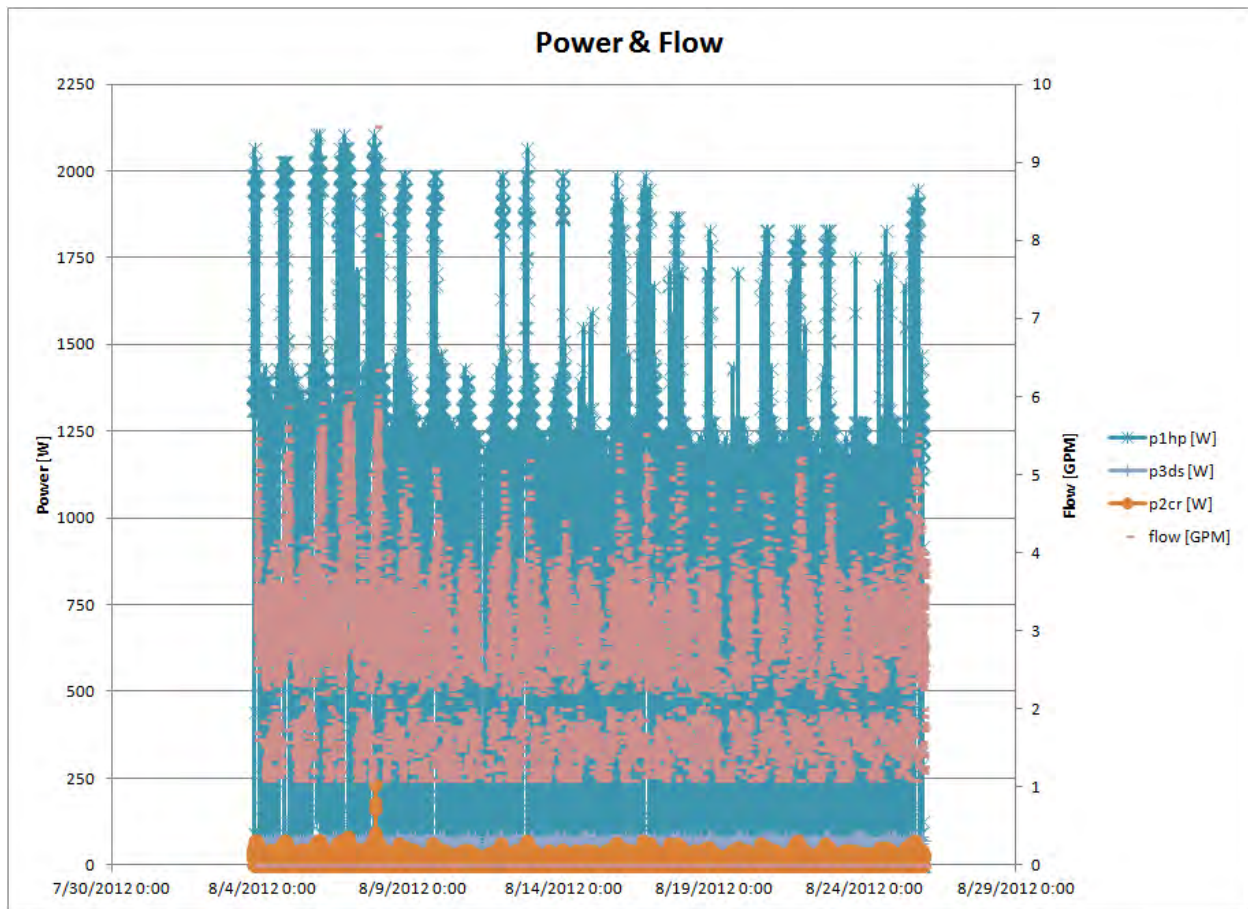


Figure B-6-4-1. Measured power and flow rate

8764 minutes (~6 days) data is missing in this month. Data is missing since 8/25/2012 21:56.

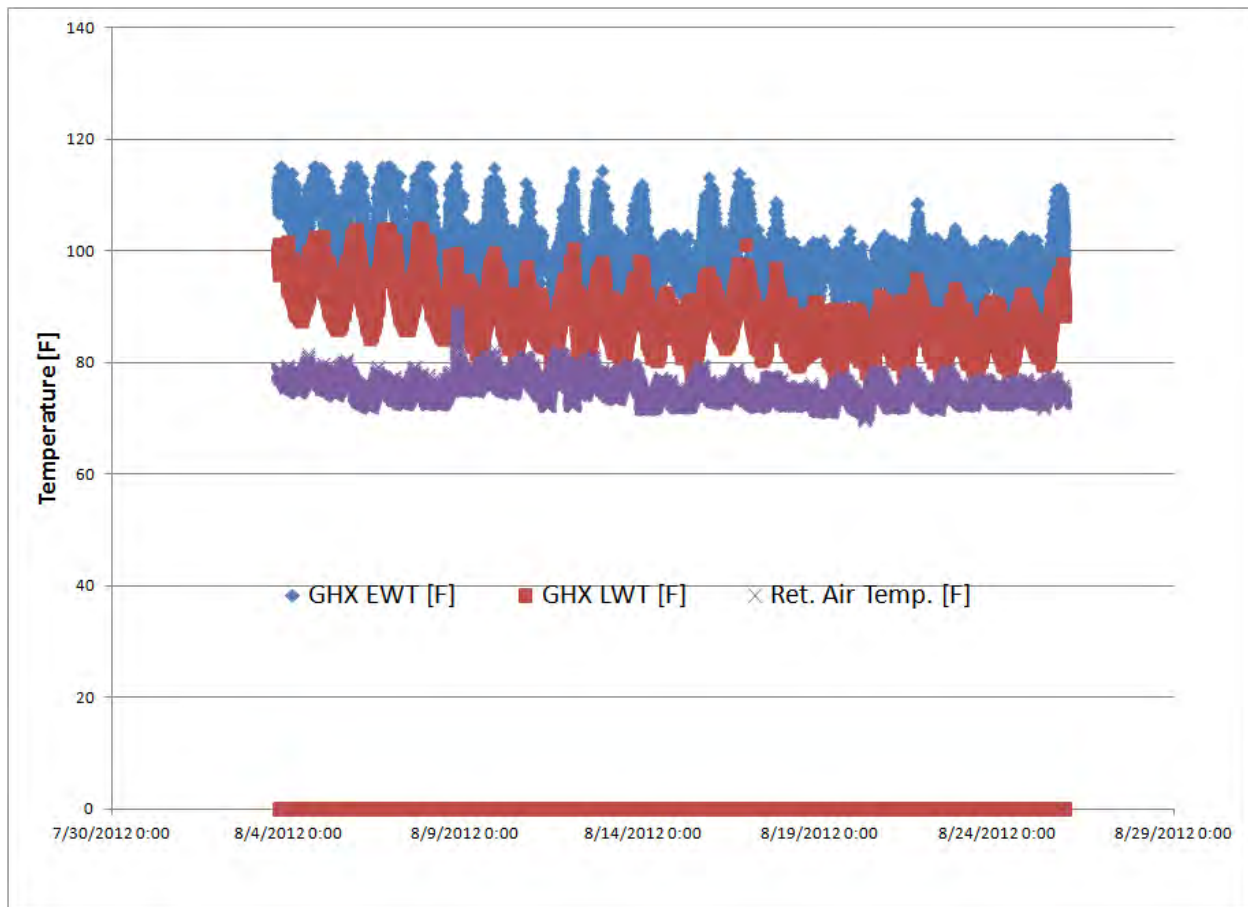


Figure B-6-4-2. Measured room and loop temperatures

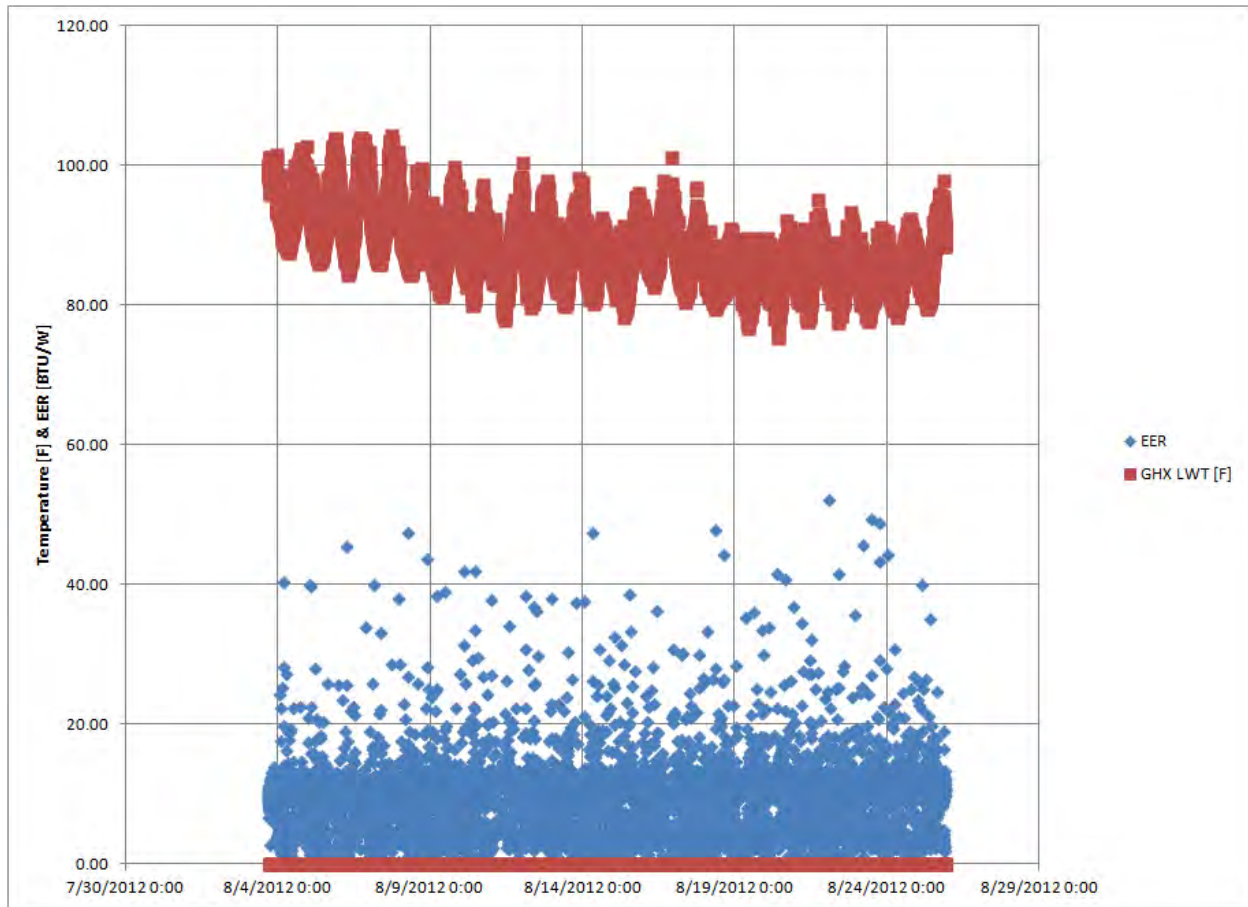


Figure B-6-4-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

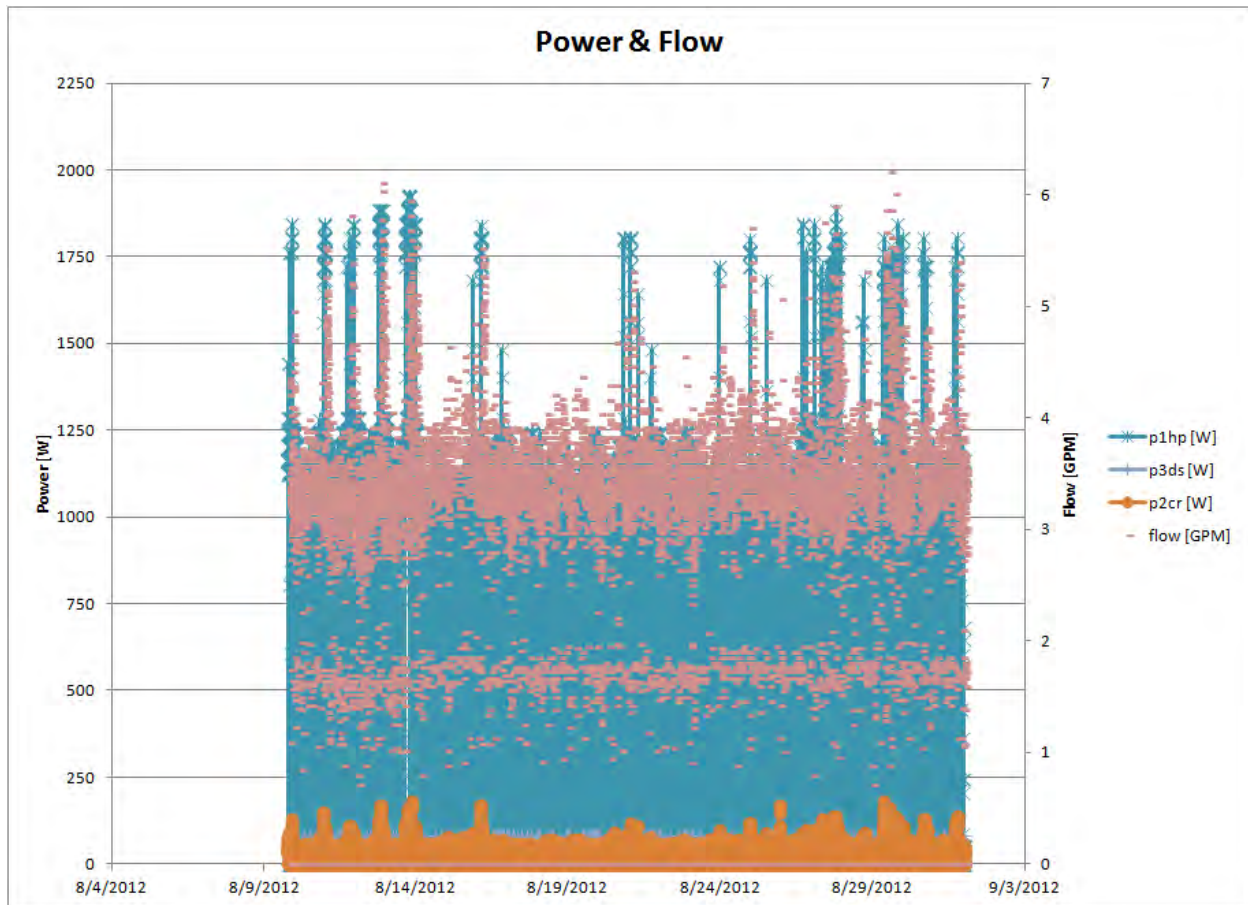


Figure B-6-5-1. Measured power and flow rate

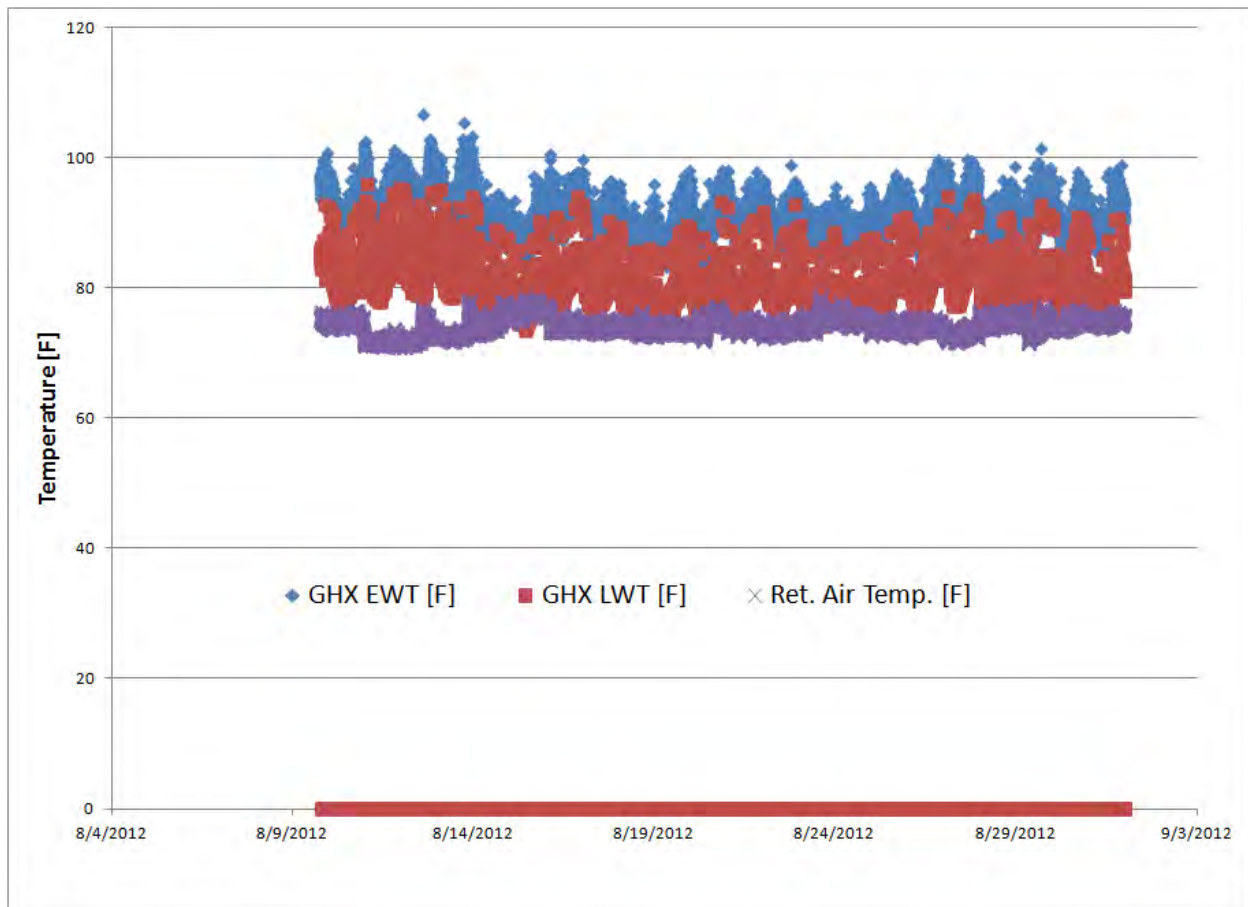


Figure B-6-5-2. Measured room and loop temperatures

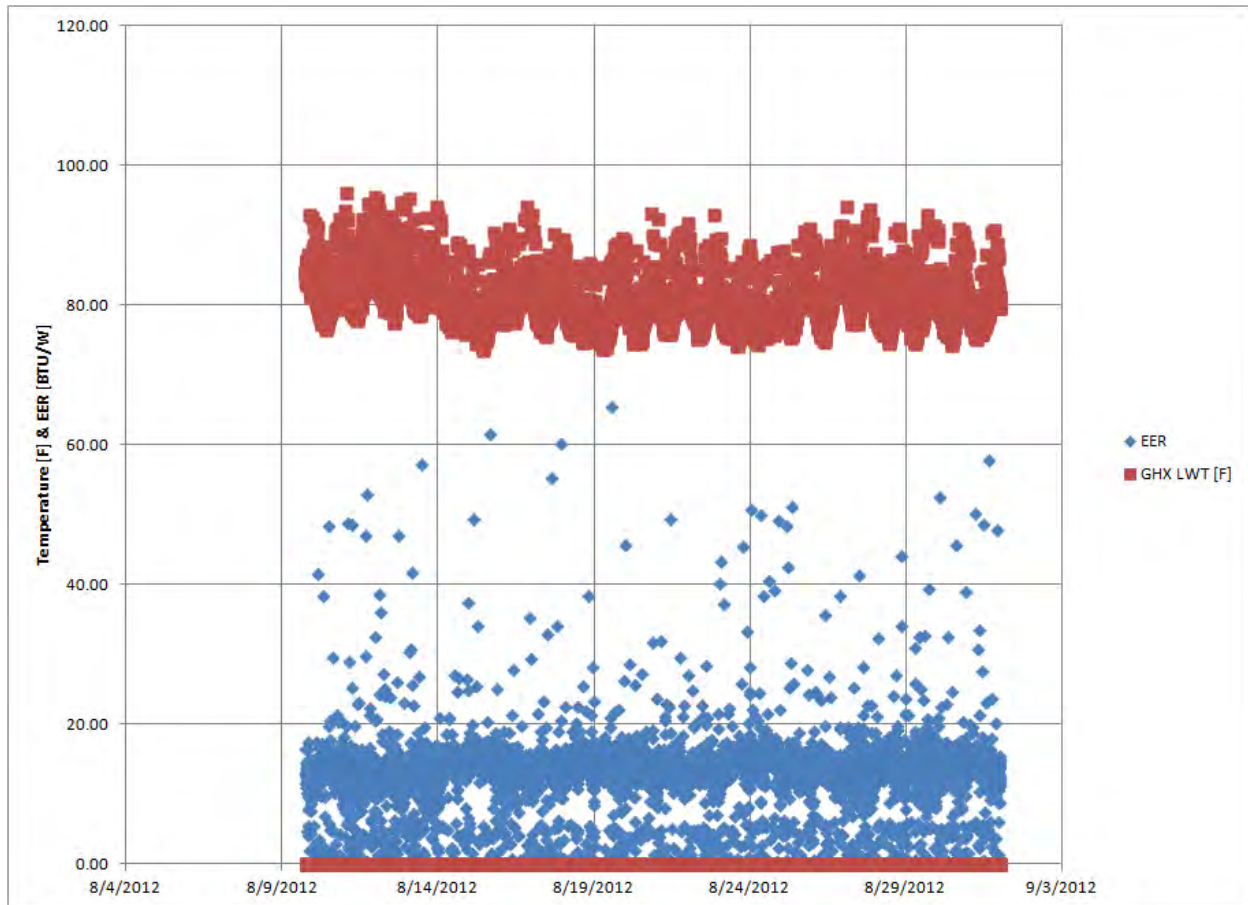


Figure B-6-5-3. Calculated system COP (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

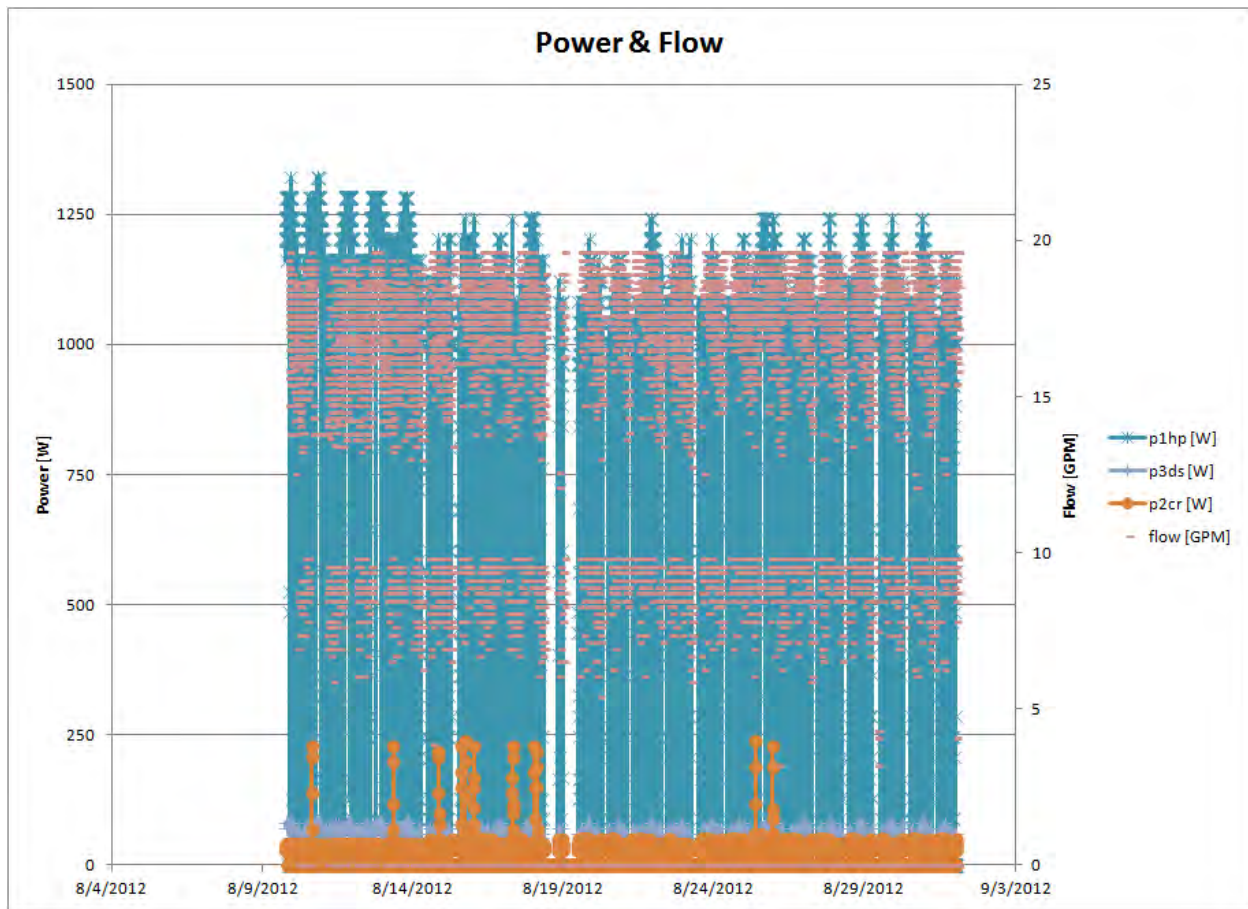


Figure B-6-6-1. Measured power and flow rate

Average flow rate is 16.7 GPM (excluding all the zero flow rate data). The high flow rate measurements are not valid since the cooling/heating capacity calculated with the measured flow rate is more than double the nominal capacity of the 2 ton heat pump unit.

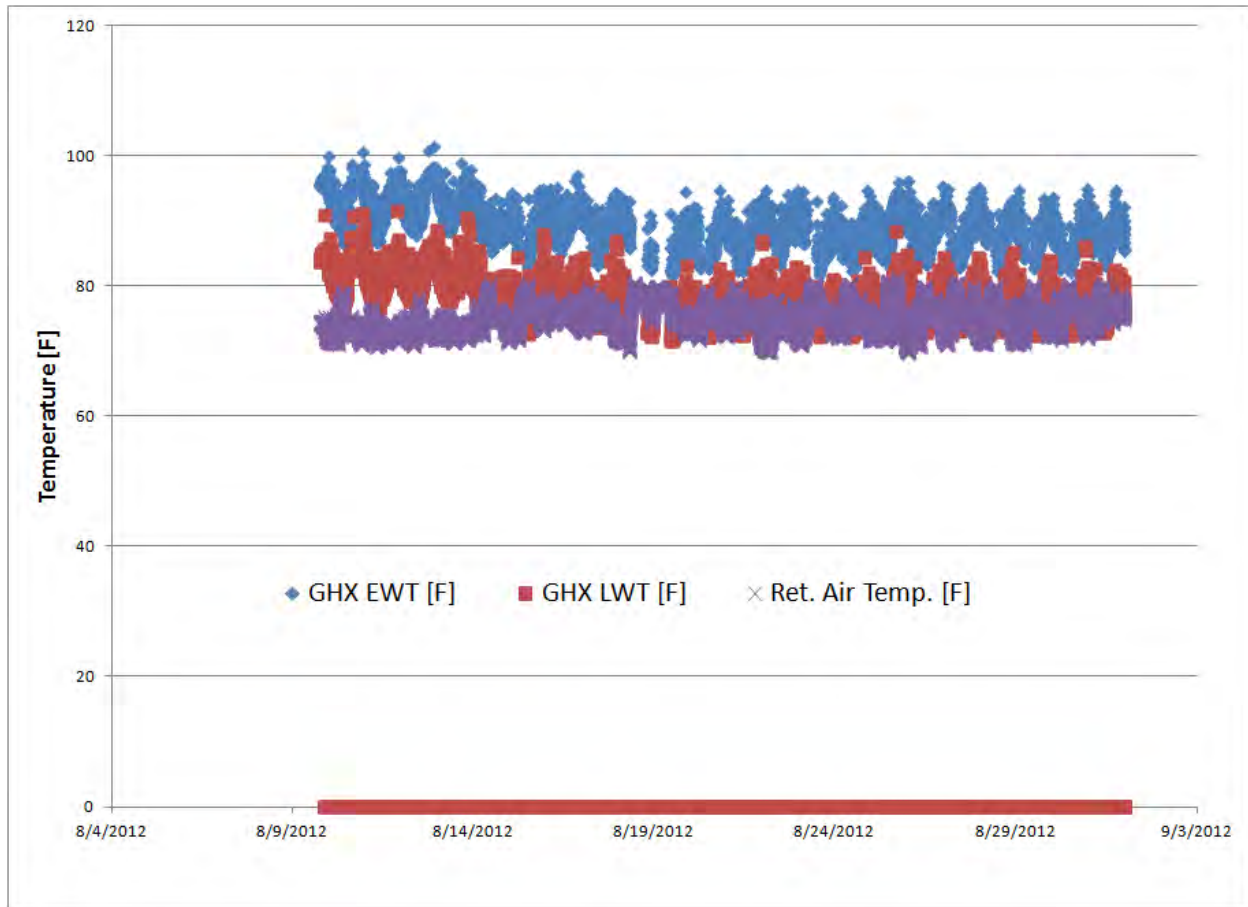


Figure B-6-6-2. Measured room and loop temperatures

Unit 07 (928)

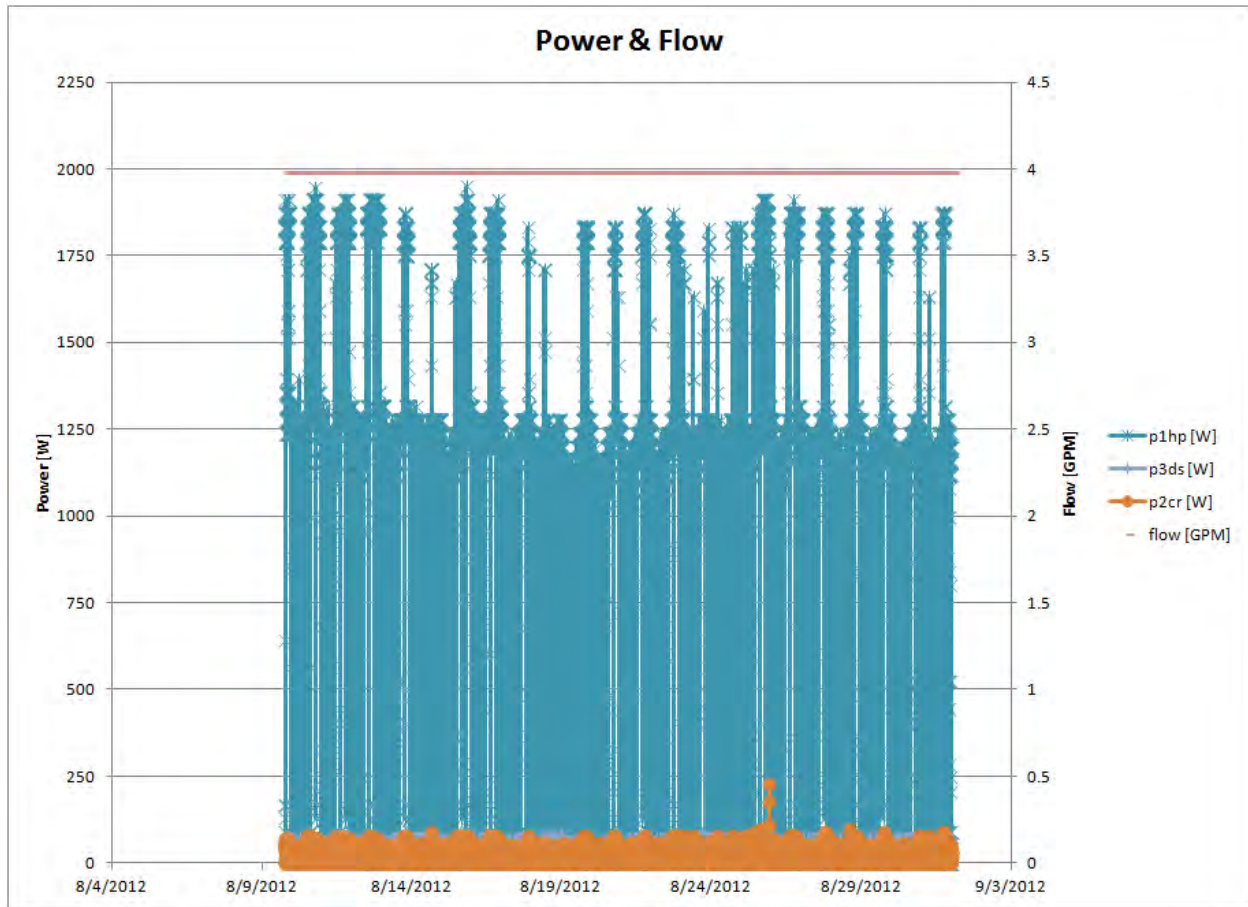


Figure B-6-7-1. Measured power and flow rate

No valid flow rate data in this month.

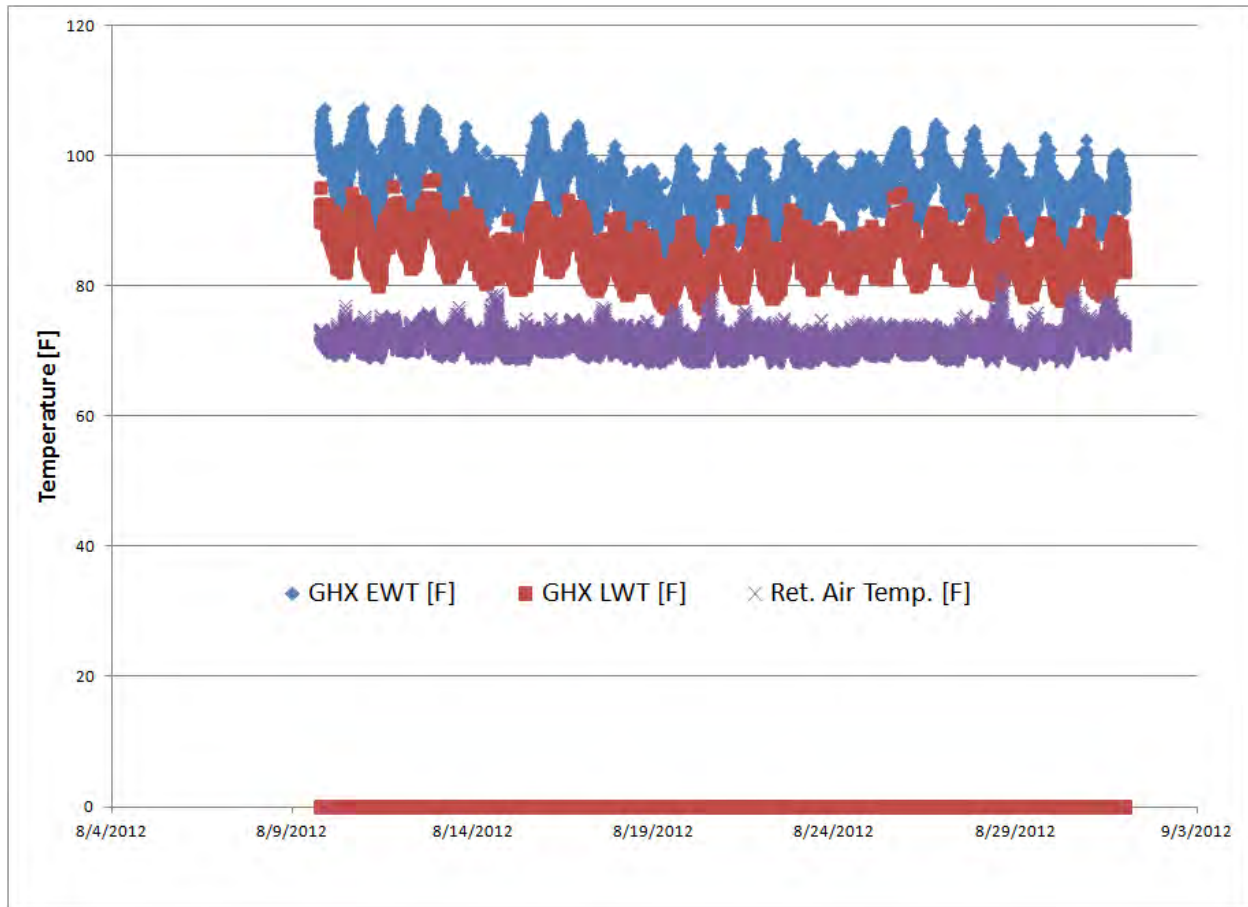


Figure B-6-7-2. Measured room and loop temperatures

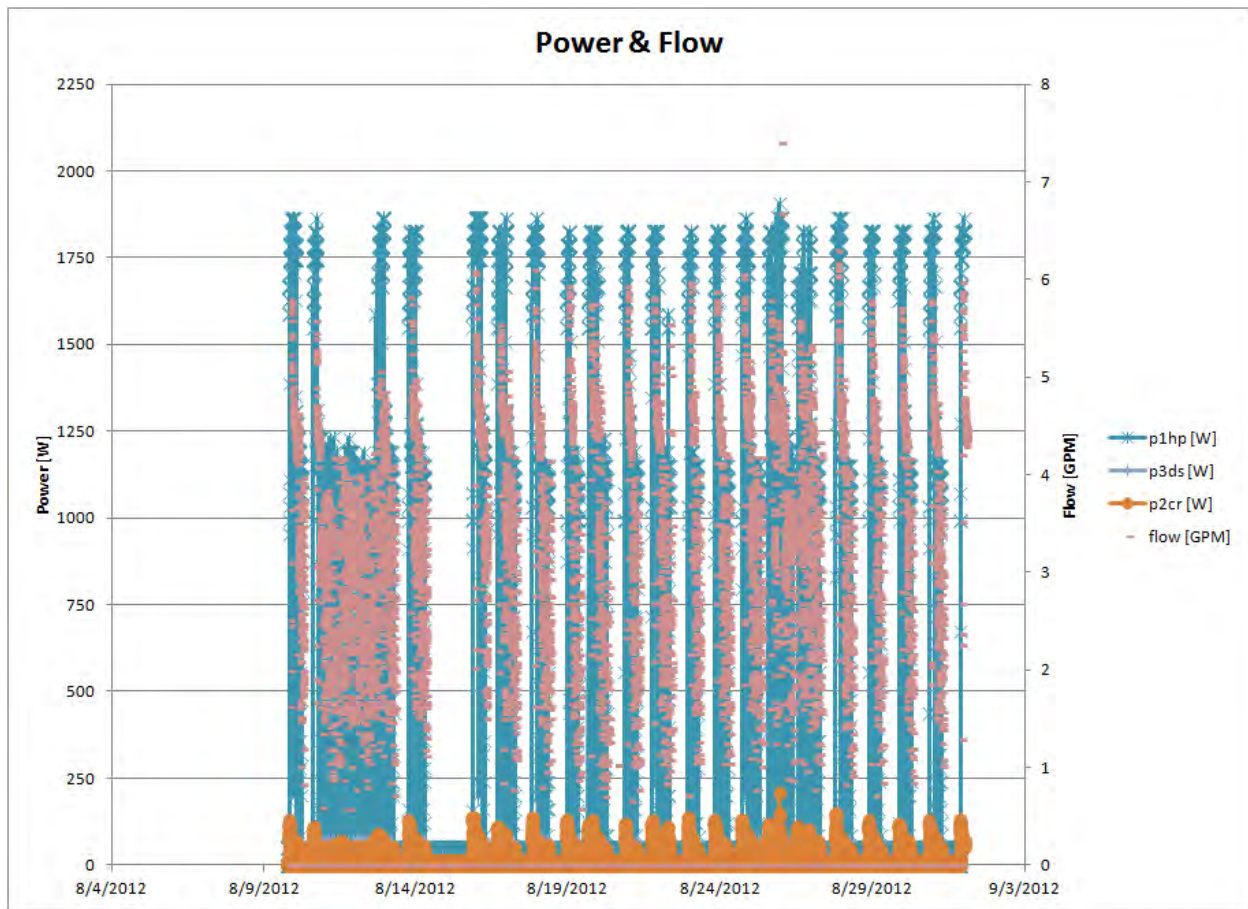


Figure B-6-8-1. Measured power and flow rate

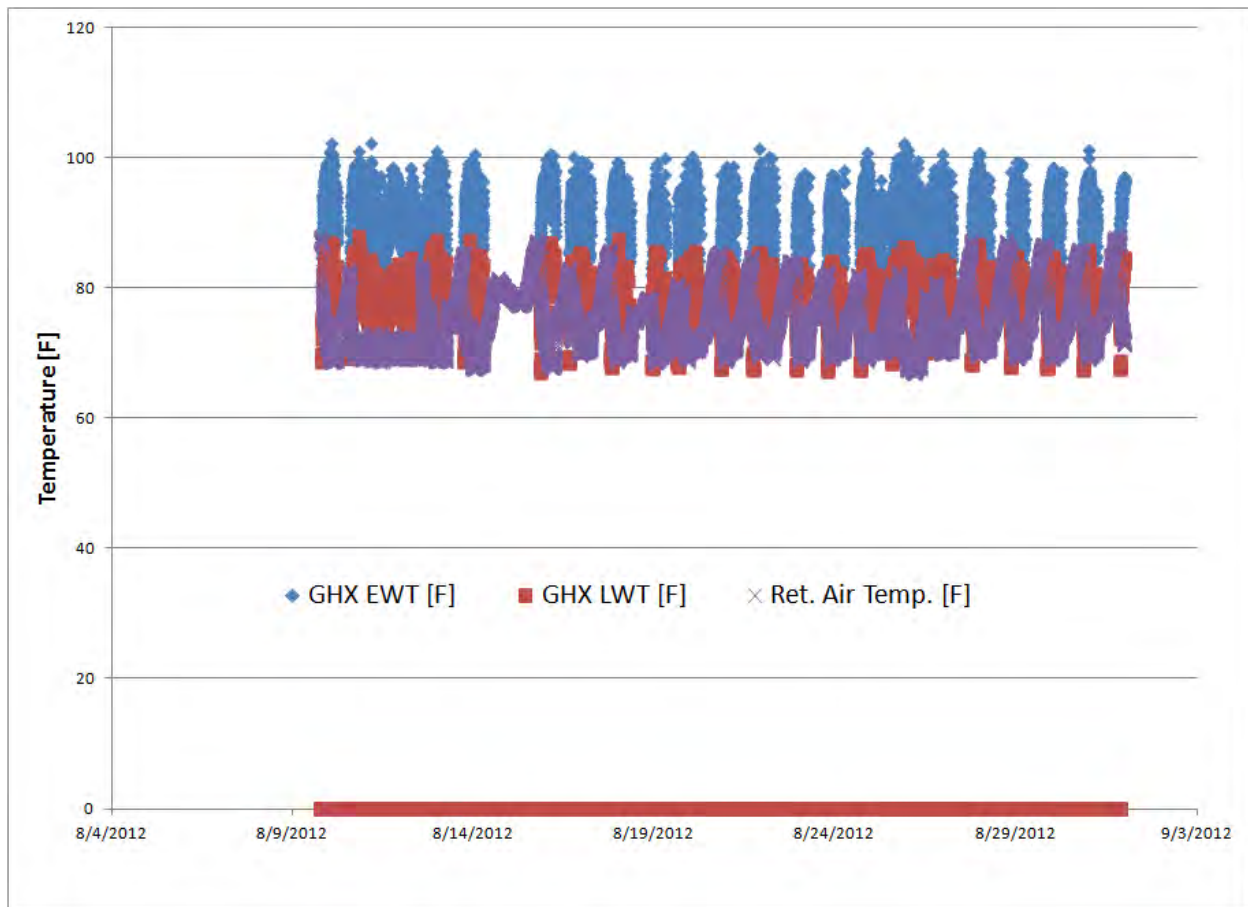


Figure B-6-8-2. Measured room and loop temperatures

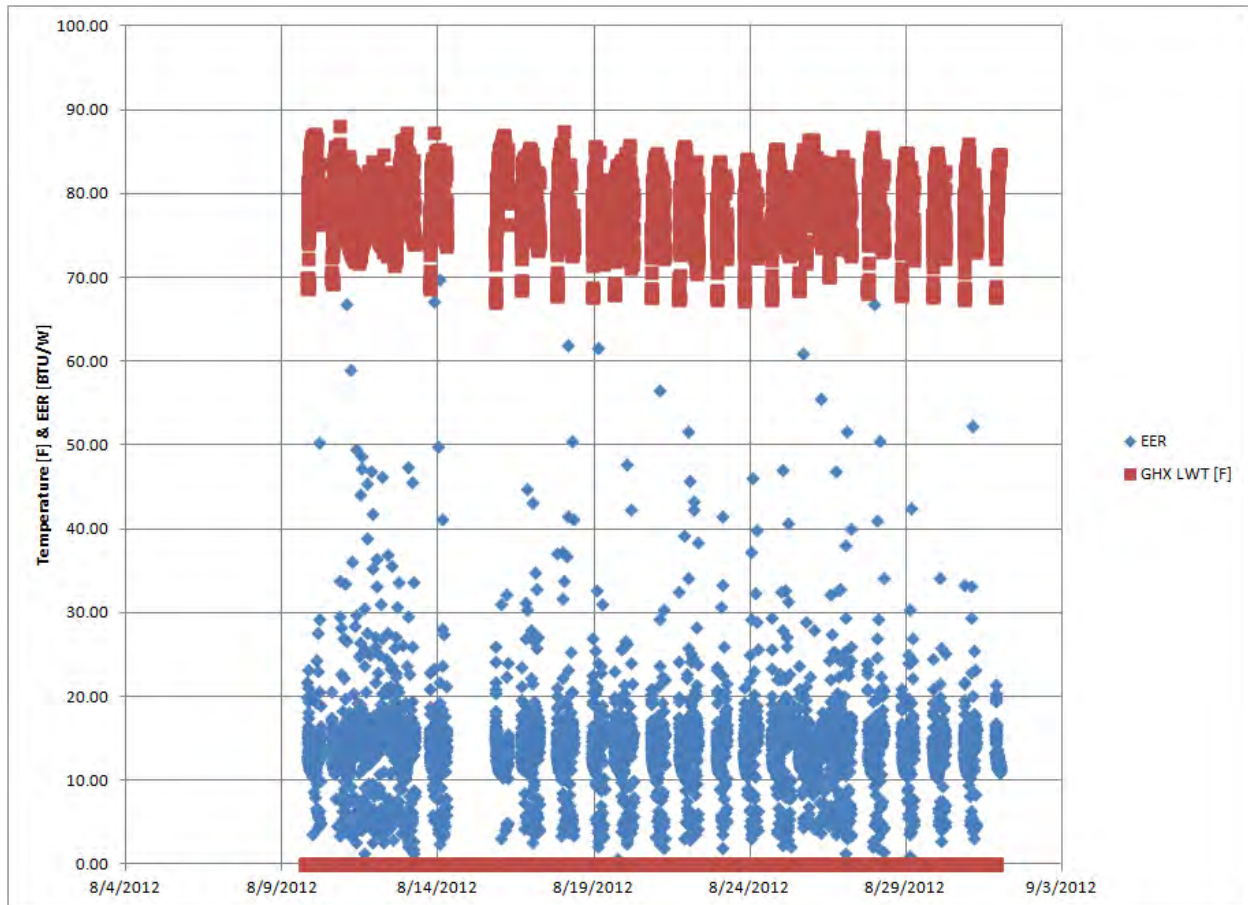


Figure B-6-8-3. Calculated system EER (including all the pumping and fan power, but does not separate the effect of the desuper-heater)

Unit 09 (944)

Due to the high GHX LFT experienced in July, the original GHX was added to supplement the new GHX. The data collection was discontinued since then.

Unit 10 (8528)

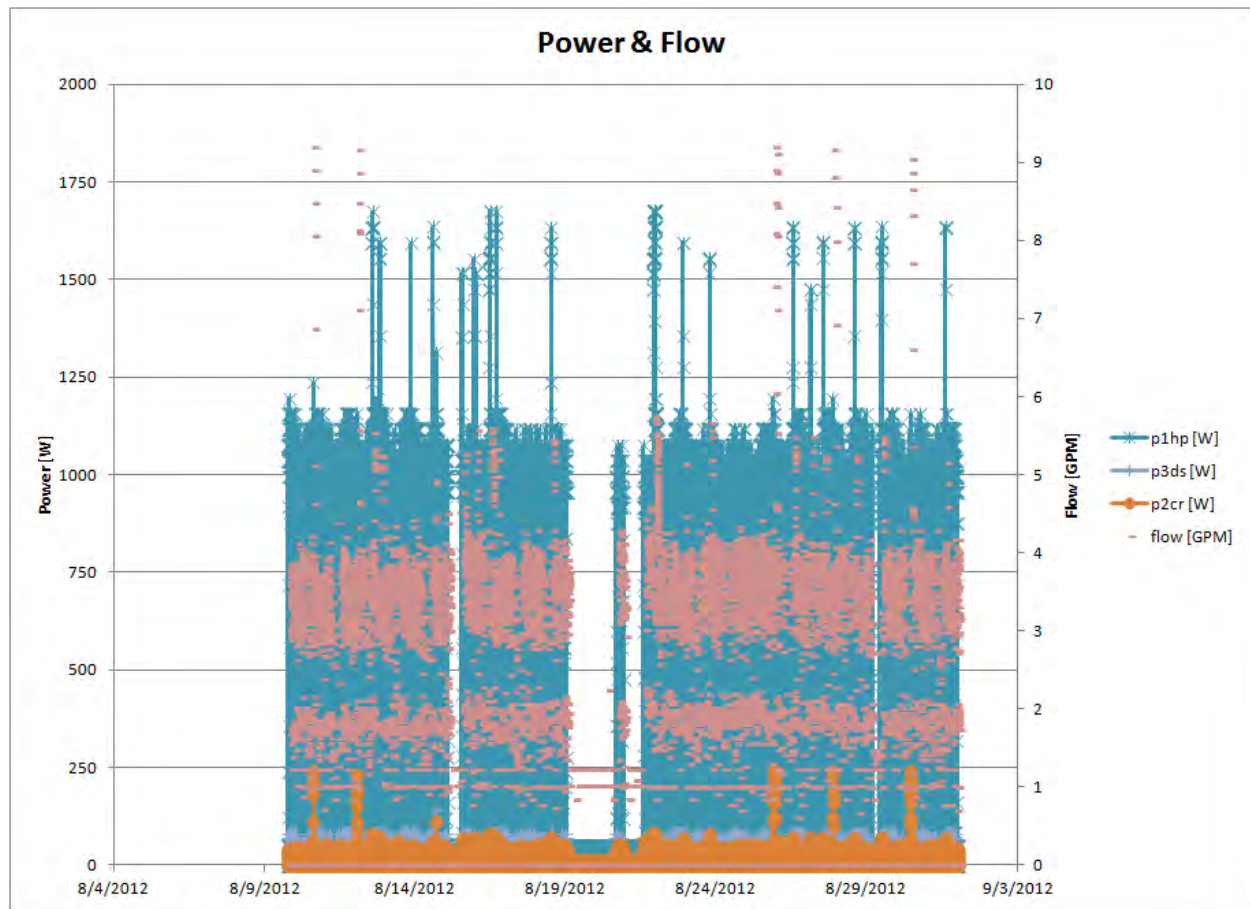


Figure B-6-10-1. Measured power and flow rate

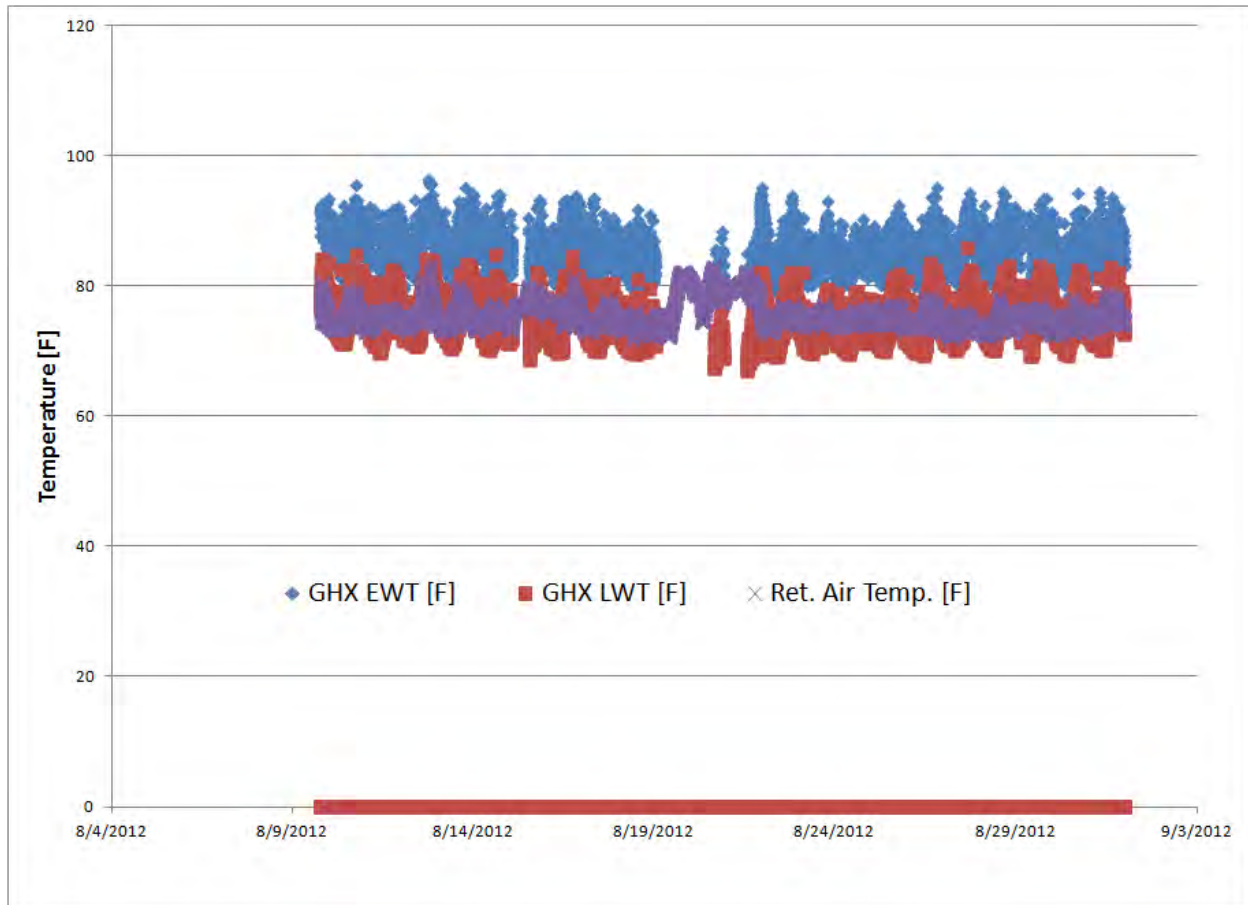


Figure B-6-10-2. Measured room and loop temperatures

It appears that the system was shut down for most time during 8/19-8/21.

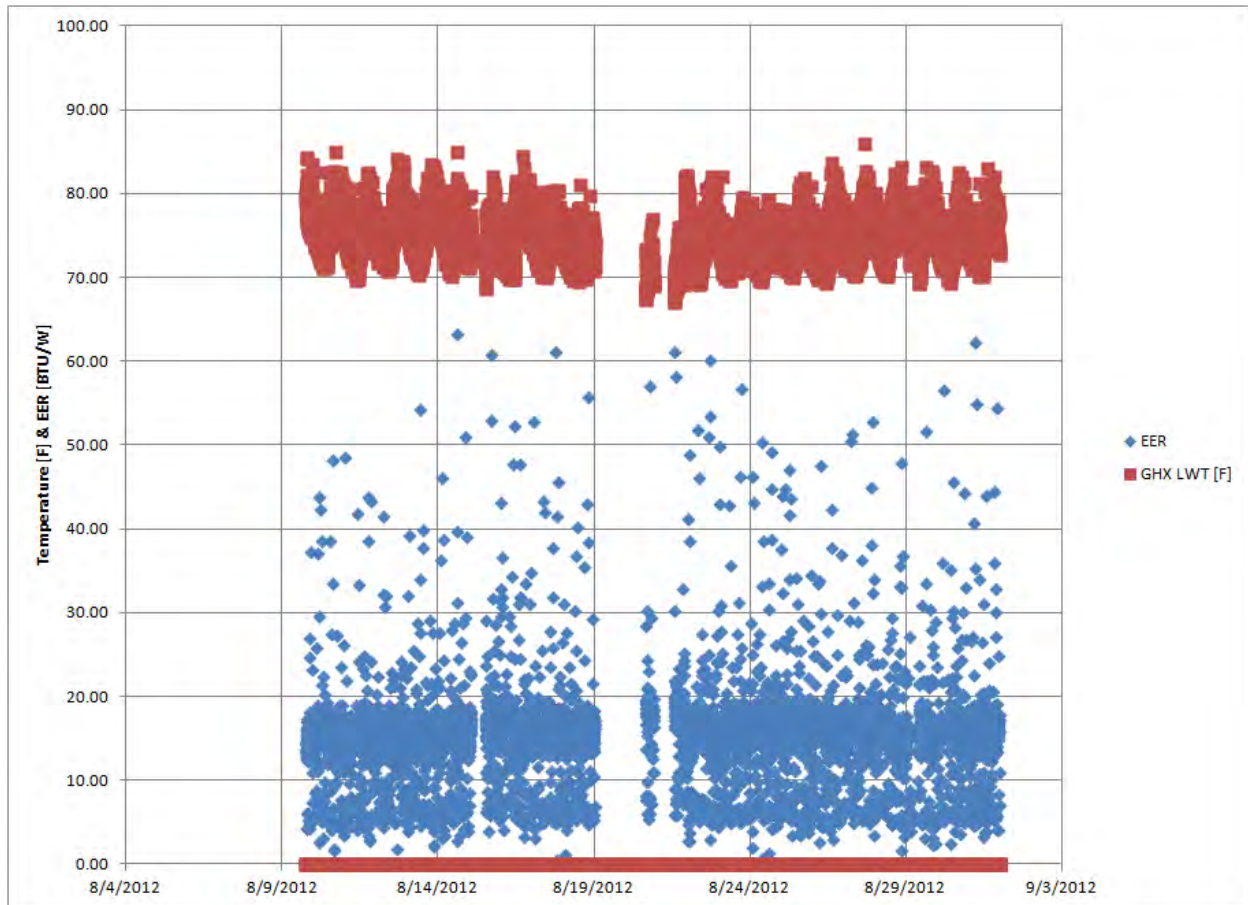


Figure B-6-10-3. Calculated system EER (including all the pumping and fan power, but does not separate the effect of the desuper-heater)